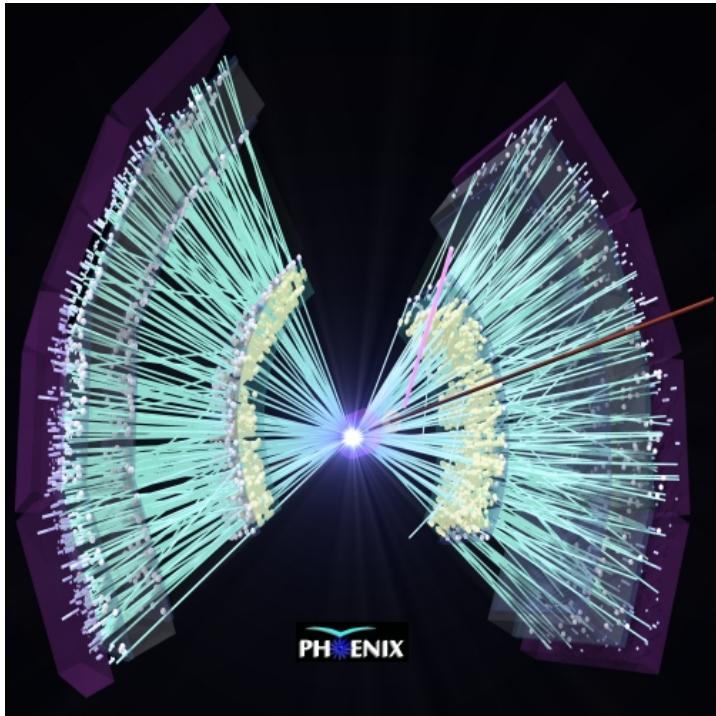


Signatures of Color Glass Condensate: Forward Azimuthal Angle Di-Hadron Correlations in PHENIX



Beau Meredith (UIUC)
For the *PHENIX* Collaboration
2010 CGC Workshop
What we have learned from RHIC

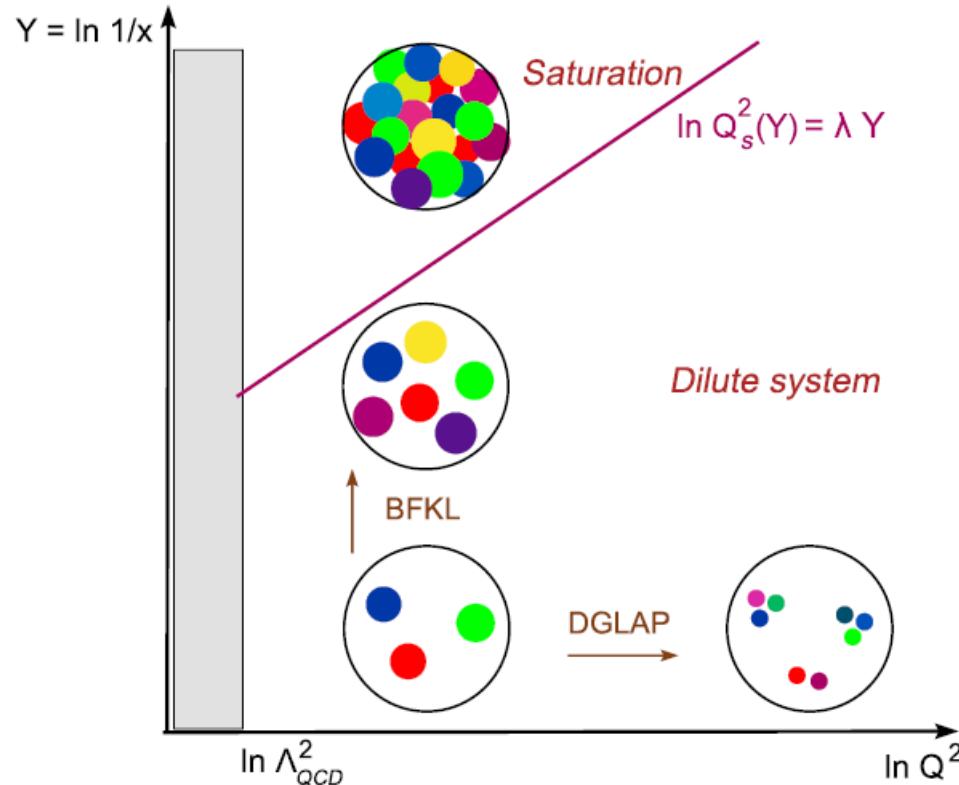


Outline

- Theory Motivation
- PHENIX Detector Subsystems
- Two-particle Correlation Measurements
- Results and Interpretation
 - Published RHIC Run3 d+Au
 - New RHIC Run8 d+Au
- Outlook



The Color Glass Condensate



See Yu.V. Kovchegov, Phys. Rev. D 61, 074018 (2000).
 For review, see F. Gelis, E. Iancu, J. Jalilian-Marian, R. Venugopalan, arXiv:1002.0333

gluon density $n(Y, k_T)$ saturates for large densities at small x :

Non-linear evolution eqn.

$$\frac{\partial n}{\partial Y} \cong \lambda \alpha_S n + v \alpha_S \partial_t^2 n - \mu \alpha_S^2 n^2$$

\downarrow
g emission
 \downarrow
diffusion
 \downarrow
g-g merging

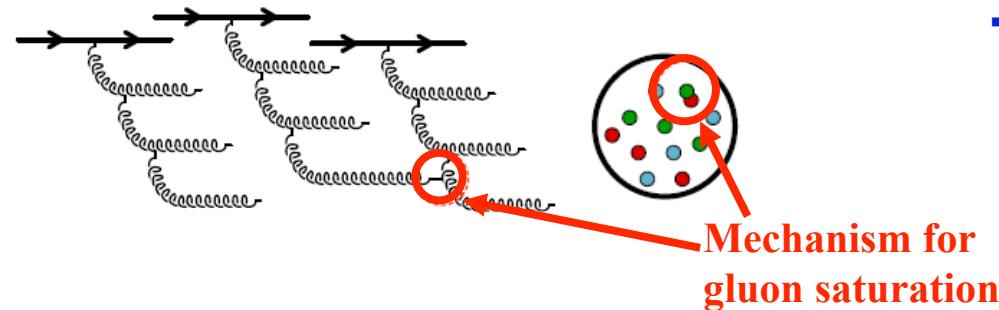
g-g merging large if $\alpha_S n \propto 1$

→ saturation scale, Q_s

→ nuclear enhancement $\sim A^{1/3}$

→ increasing gluon density $\sim 1/x^\lambda$

$$Q_s \propto A^{1/3} / x^\lambda$$



CGC Effects at RHIC ($\sqrt{s_{NN}} = 200 \text{ GeV}$)

- Probe low x gluons at **forward rapidities**

$$x_g = \frac{p_{T1}e^{-y_1} + p_{T2}e^{-y_2}}{\sqrt{s}}$$

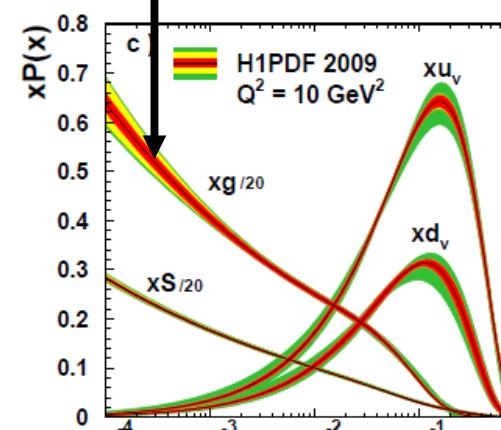
- Use **deuteron-gold (d+Au) collisions vs p+p**

- Difference is nuclear enhancement factor in saturation scale, $A^{1/3}$

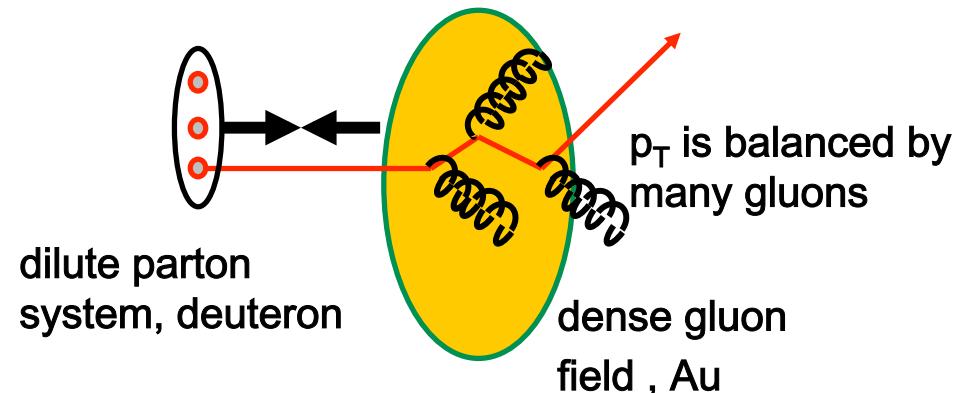
- Signatures of CGC

- **suppression** of nuclear modification factors
- **angular decorrelations** of di-jet signals (di-hadron $\Delta\phi$ correlations)
 - Disappearance of the away-side peak in when $Q^2 \sim Q_s^2$

Gluon distribution function from HERA



F.D. Aaron et al, [H1 Collaboration]
Eur. Phys. J. C 64, 561 (2009)

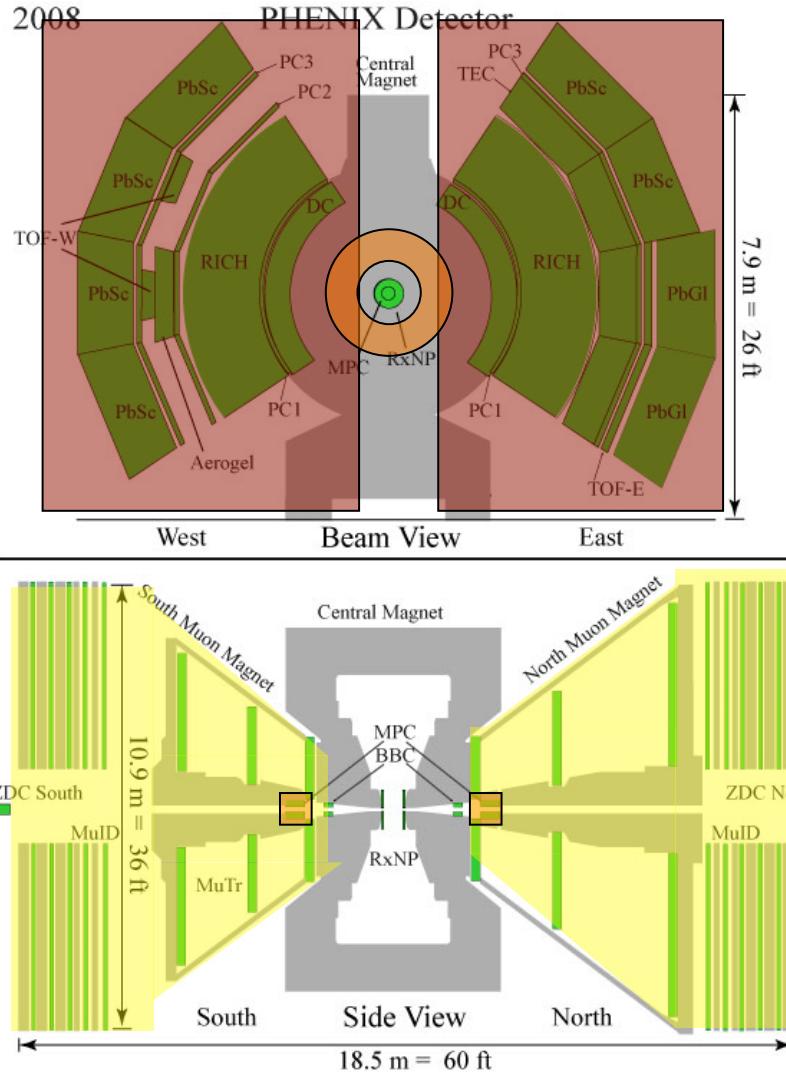


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PHENIX Detector at RHIC



Central Arms $|\eta| < 0.35$

- Charged hadrons
- Neutral pions / η
- Heavy Flavor electrons
- Direct Photon
- J/Psi

Muon Arms $1.2 < |\eta| < 2.4$

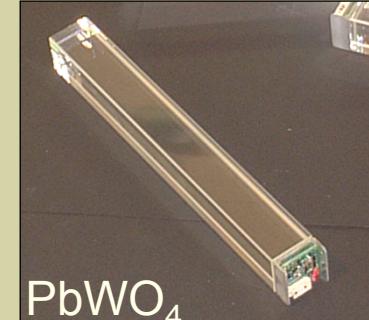
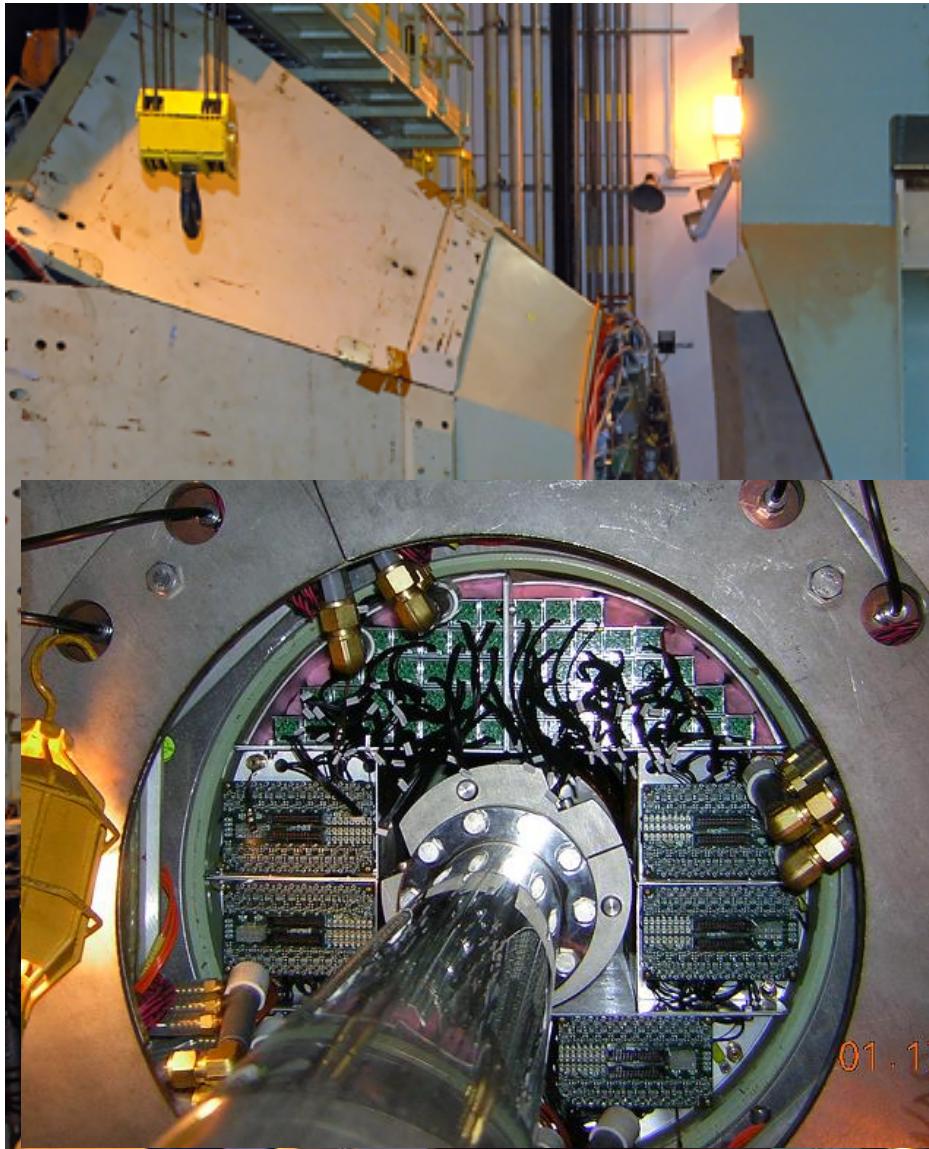
- Unidentified charged hadrons
- Heavy Flavor muons
- J/Psi

Muon Piston Calorimeter

- $3.1 < |\eta| < 3.9$
- Neutral pions / η



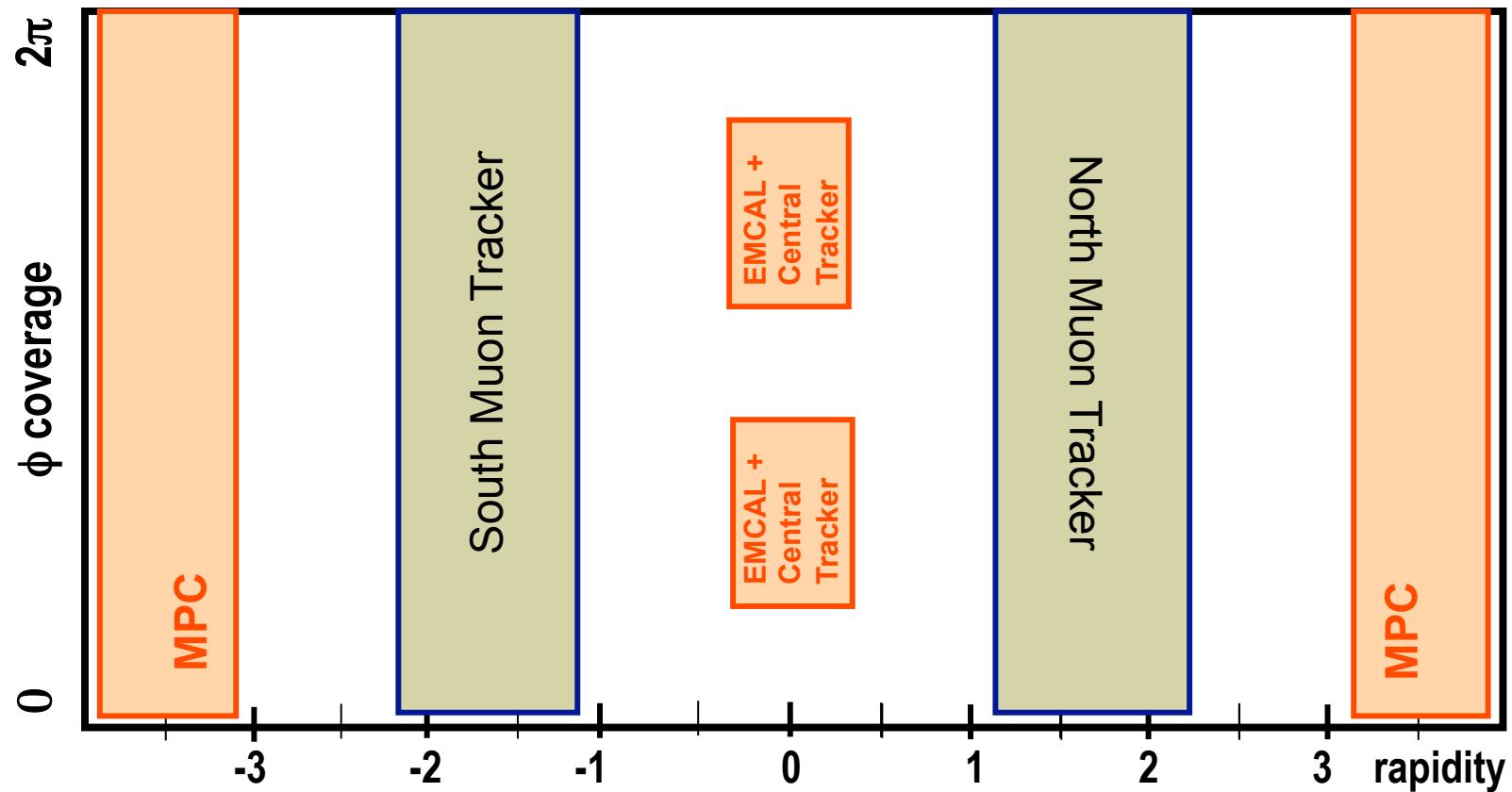
PHENIX Muon Piston Calorimeter



PbWO_4

Density	8.28 g/cm ³
Size	2.2x2.2x18 cm ³
Length	20 X0, 0.92 λ
Weight	721.3 g
Moliere radius	2.0 cm
Radiation Length	0.89 cm
Interaction Length	22.4 cm
Light Yield	~10 p.e./MeV @ 25° C
Temp. Coefficient	-2% / °C
Radiation Hardness	1000 Gy
Main Emission Lines	420-440, 500 nm
Refractive Index	2.16

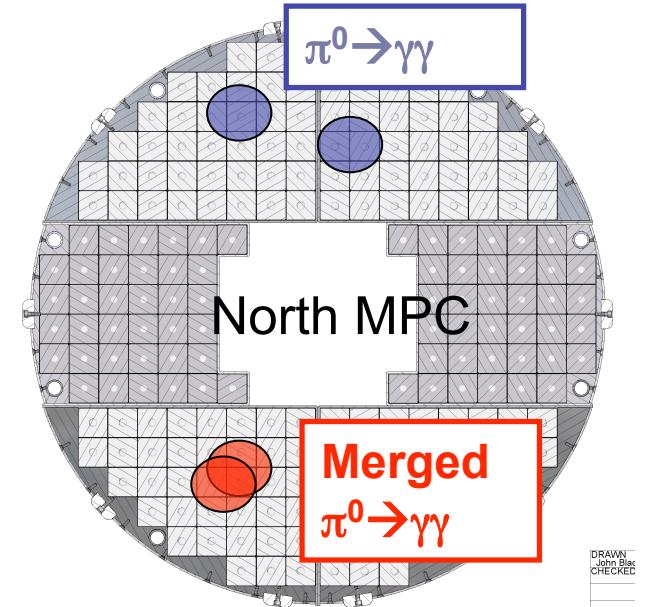
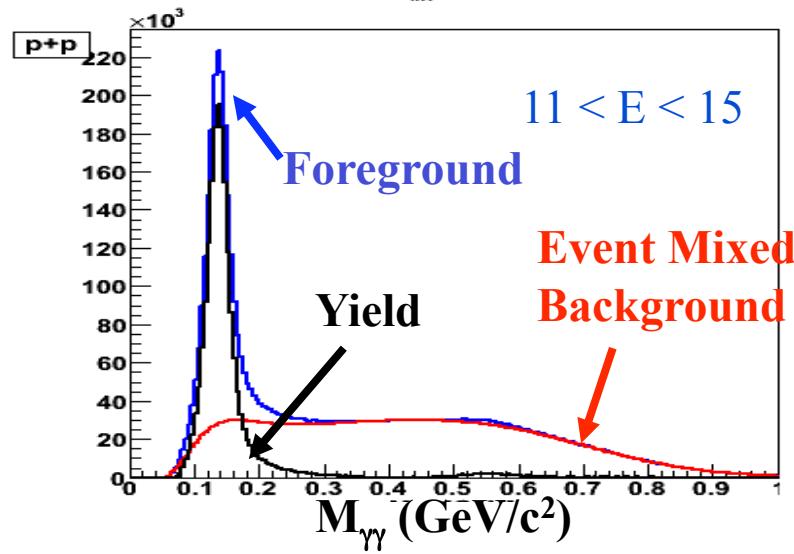
Small cylindrical hole in Muon Magnet Piston, Radius 22.5 cm and Depth 43.1 cm



- MPCs installed in 2005-2006
- Increase PHENIX acceptance for calorimetry by a factor of 4
(with a detector more than 10 times smaller)



Forward Muon Piston Calorimeters



- π^0 ID up to $E \sim 20$ GeV with MPCs ($3.1 < |\eta| < 3.9$)
 - Limitations: tower separation and merging effects
 - Use π^0 s for $7 \text{ GeV} < E < 22 \text{ GeV}$
 - p_T max $\sim 2 \text{ GeV}/c$
 - Use event mixing to subtract bg
- Single Clusters for $E > 15$ GeV
 - Dominated by π^0 ($\sim 85\%$)
 - Access higher p_T



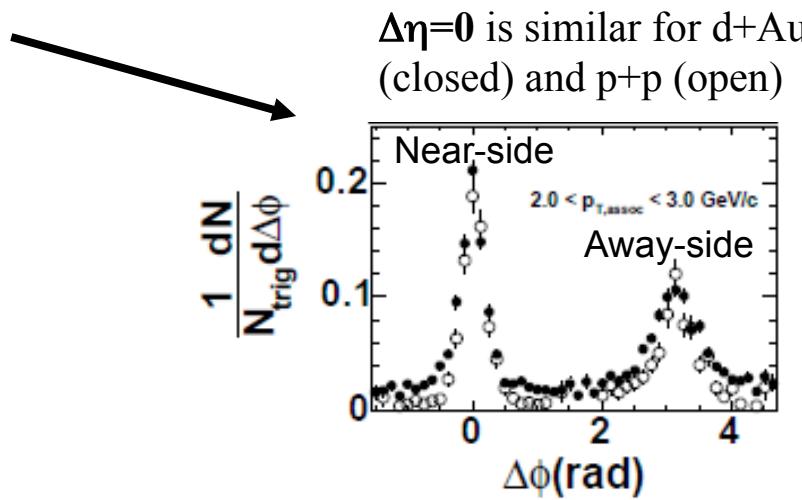
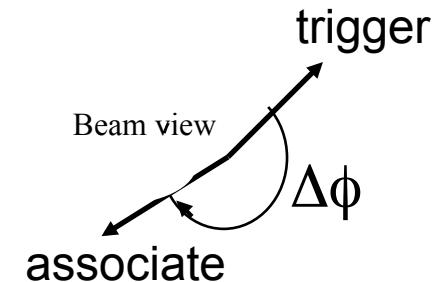
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Azimuthal Angular Correlations

- Measure $\Delta\phi$ of all particle pairs
 - Define **trigger particle** (basically the leading p_T particle – indicates jet) and **associate particle** (lower p_T)
- **Signals of saturation** are suppression and/or broadening of away-side peak in d+Au relative to p+p
- p+p, d+AuCentral rapidity correlations are similar (RHIC Run3)

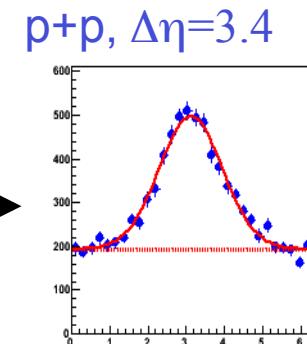


S.S Adler et al, Phys. Rev. C 73:054903,2006.



Forward Rapidity Correlations

- Use PHENIX forward detectors
- New results from RHIC run8 $\sqrt{s_{NN}} = 200 \text{ GeV}$
 - d+Au ($L_{\text{int}} = 80 \text{ nb}^{-1}$)
 - p+p ($L_{\text{int}} = 5.2 \text{ pb}^{-1}$) from RHIC Run8
- Measure two sets of different angular correlations
 - **Rapidity-separated (forward/central)**
 - Predicted to be sensitive to saturation effects in d+Au
 - **Both particles forward (forward/forward)**
 - Lowest x (strongest test for saturation in d+Au)



$\Delta\phi$



How do we Quantify Suppression?

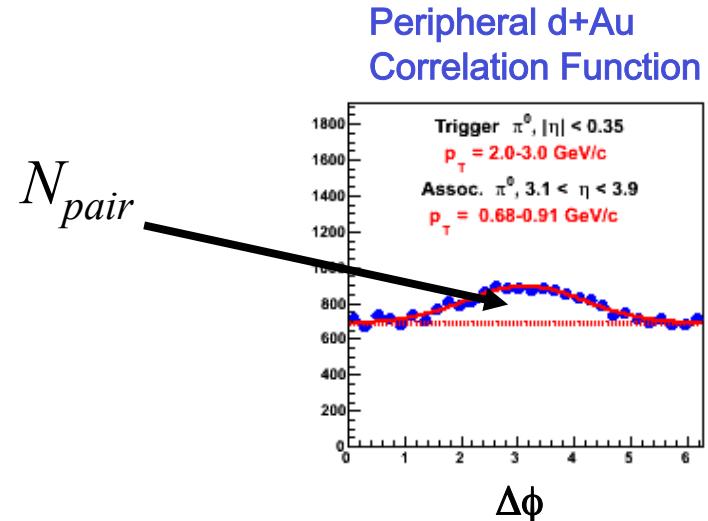
- “Conditional Yield”
 - Number of di-jet particle pairs per trigger particle

$$CY = \frac{N_{pair}}{N_{trig} \epsilon_{assoc}}$$

Acceptance x efficiency

Nuclear Modification factor

$$I_{dA} = \frac{CY_{dA}}{CY_{pp}}$$



- Possible indicators of gluon saturation
 - $I_{dA} < 1$
 - Angular decorrelation of widths



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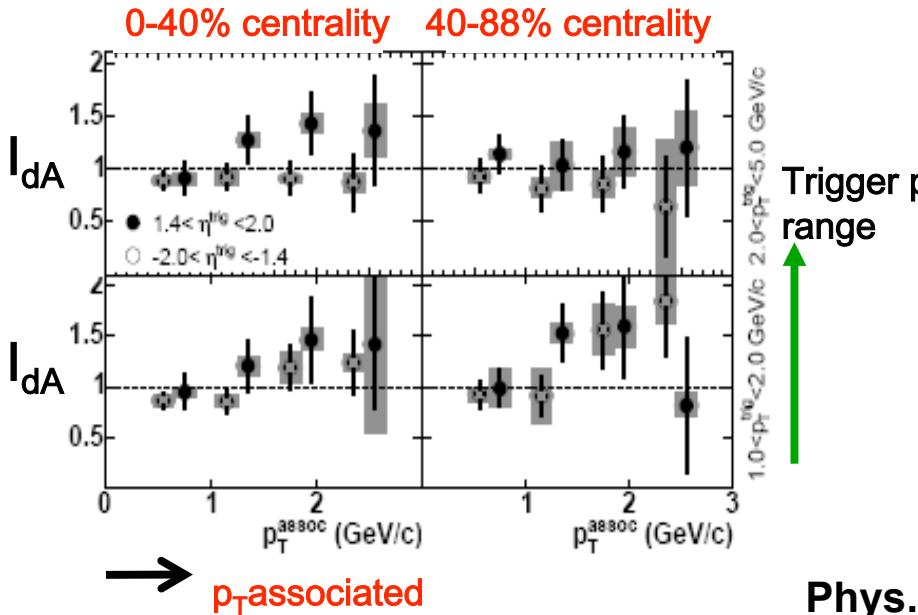


I_{dA} from the PHENIX Muon Arms

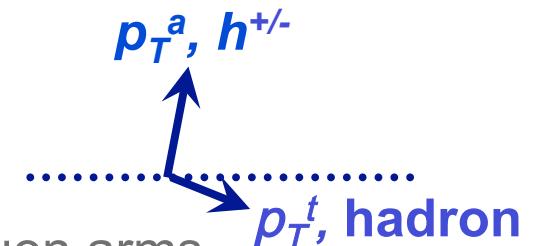
Observations at PHENIX using the 2003 d+Au sample:

- Left: I_{dA} for hadrons $1.4 < |\eta| < 2.0$, PHENIX muon arms.
correlated with $h^{+/-}$ in $|\eta| < 0.35$, central arms.
- Right: Comparison of conditional yields with different trigger particle pseudo-rapidities and different collision centralities

→ No significant suppression or widening seen within large uncertainties!



Phys.Rev.Lett. 96 (2006) 222301

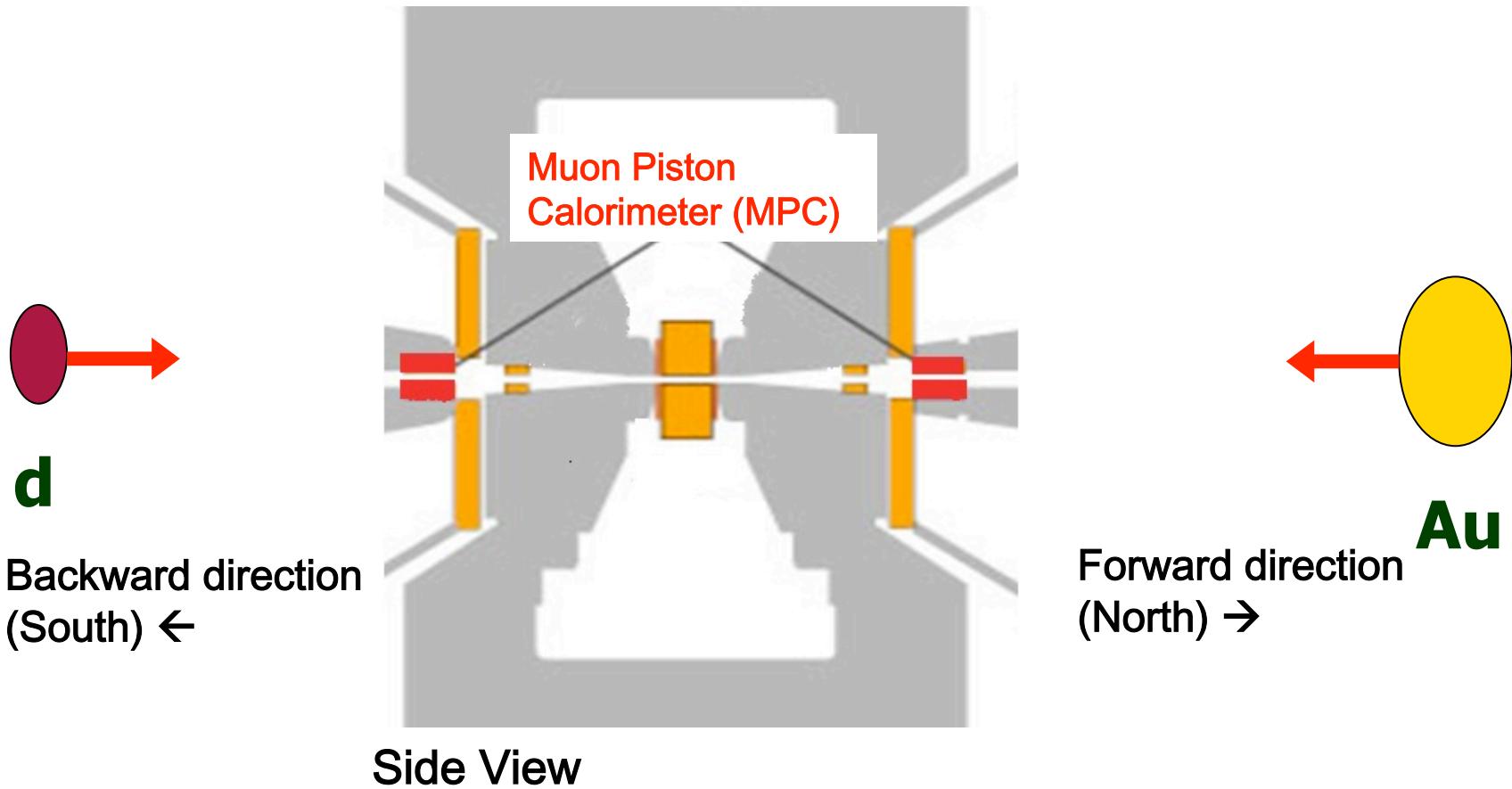


Outline

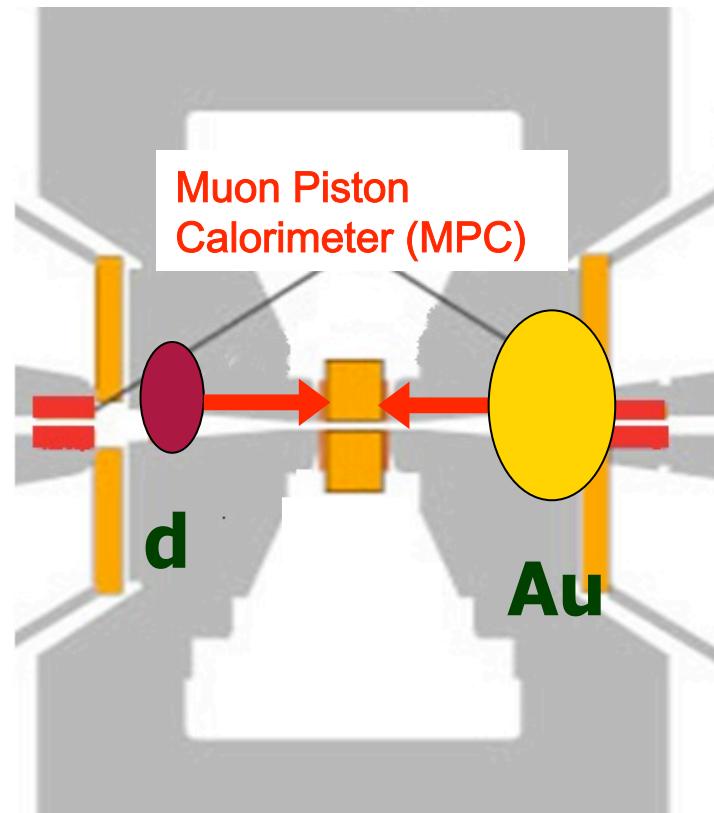
- Theory Motivation
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PHENIX central
spectrometer magnet



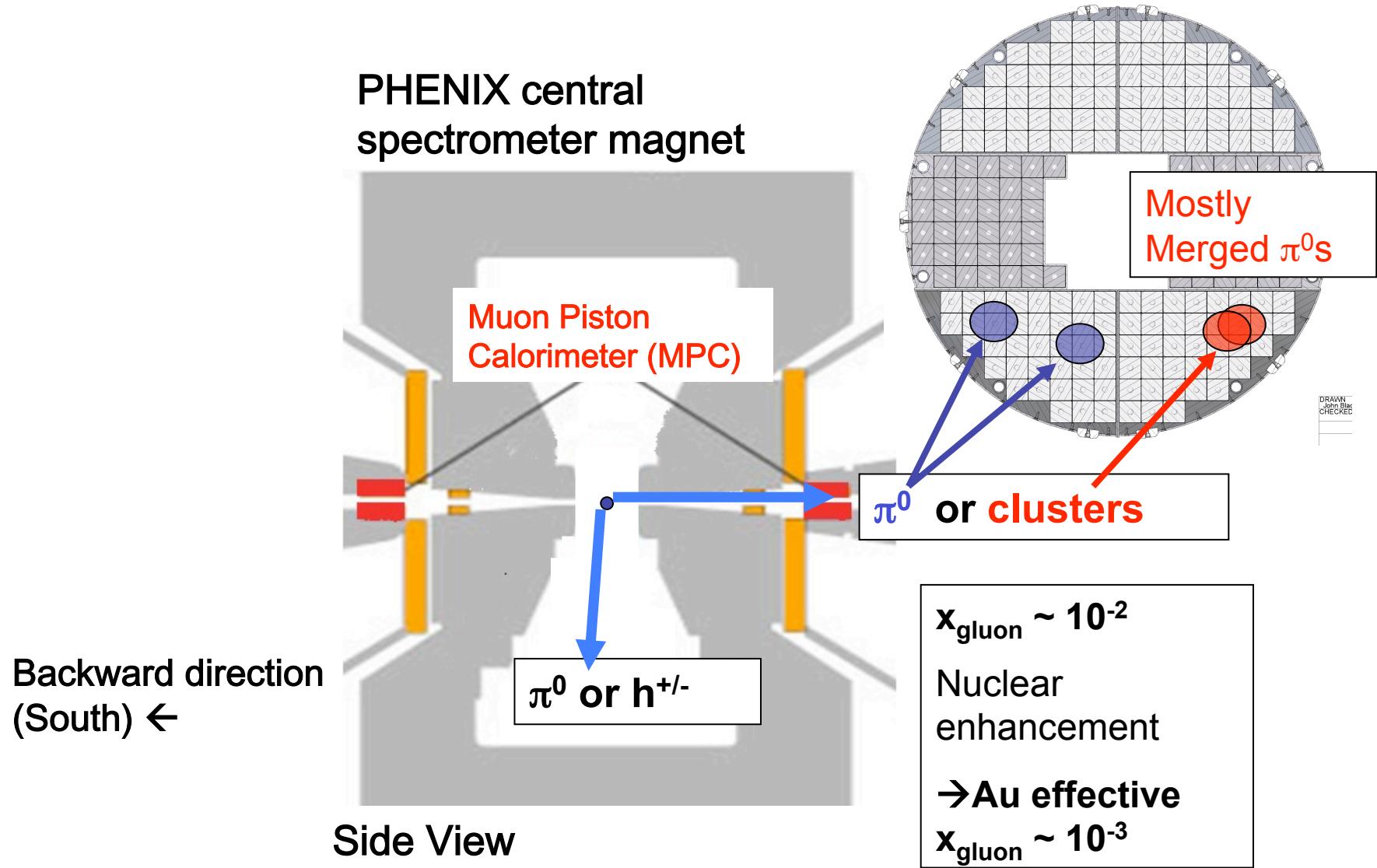
PHENIX central
spectrometer magnet



Side View



Forward Di-jet Signal with $\Delta\eta = 3.4$

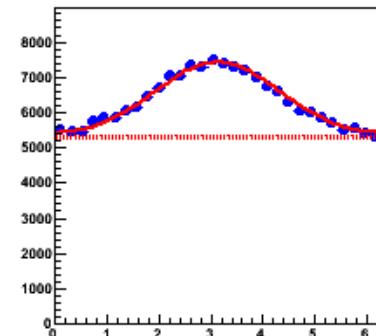


π^0 (trigger,central)/ π^0 (associate,forward)

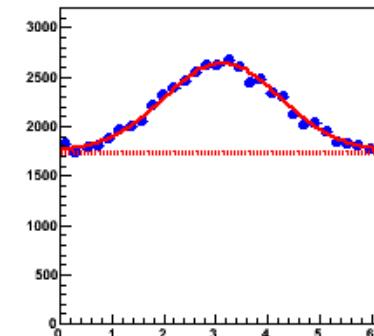
$2.0 < p_T^t < 3.0 \text{ GeV}/c$

pp

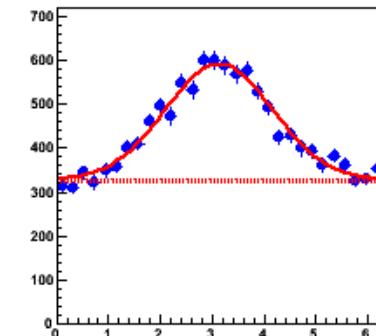
$\langle p_T^a \rangle = 0.55 \text{ GeV}/c$



$\langle p_T^a \rangle = 0.77 \text{ GeV}/c$

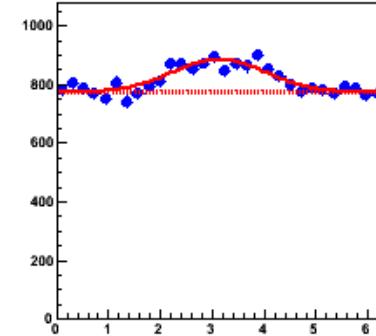
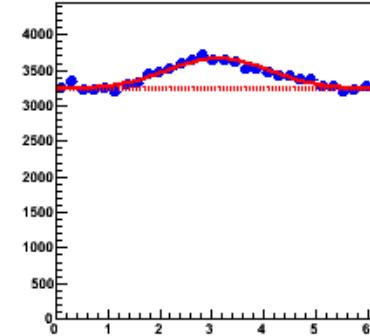
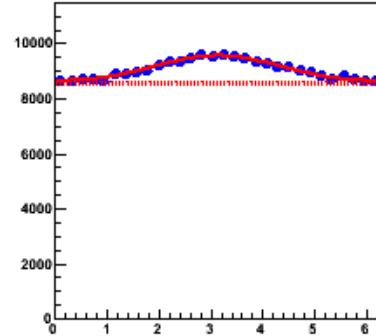


$\langle p_T^a \rangle = 1.00 \text{ GeV}/c$

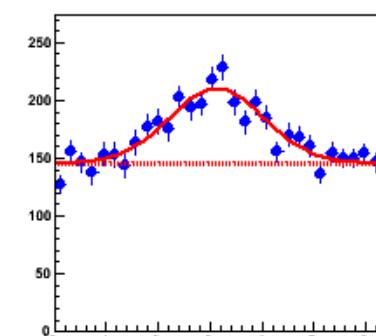
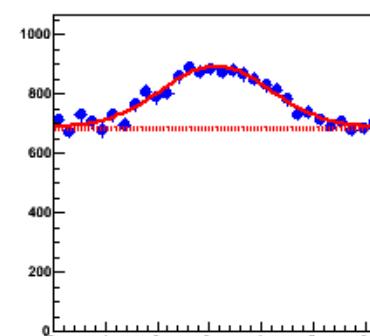
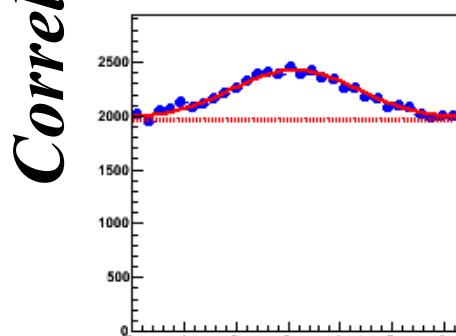


dAu 0-20%

Correlation Function



dAu 60-88%



p_T^t, π^0



$\Delta\phi$



π^0 (trigger,central)/cluster (associate,forward)

$2.0 < p_T^t < 3.0 \text{ GeV}/c$

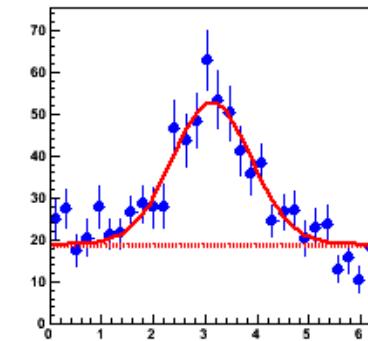
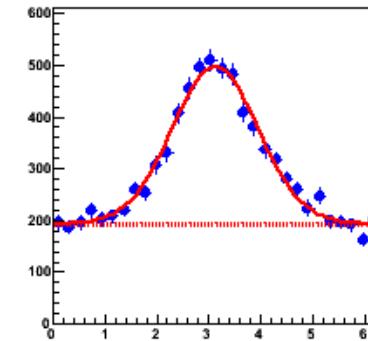
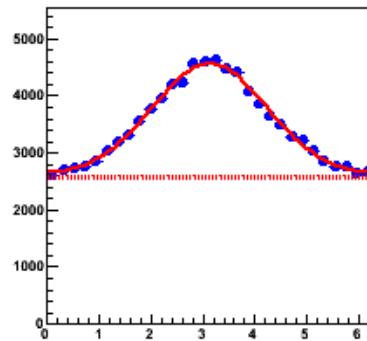
pp

$\langle p_T^a \rangle = 1.09 \text{ GeV}/c$

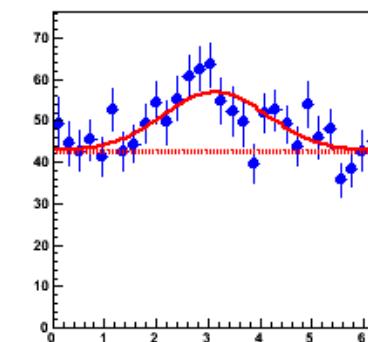
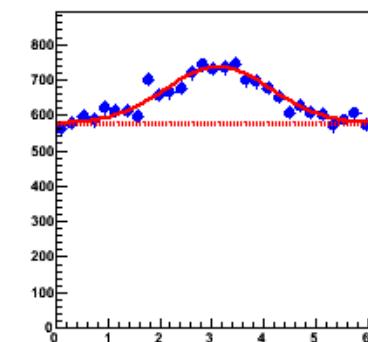
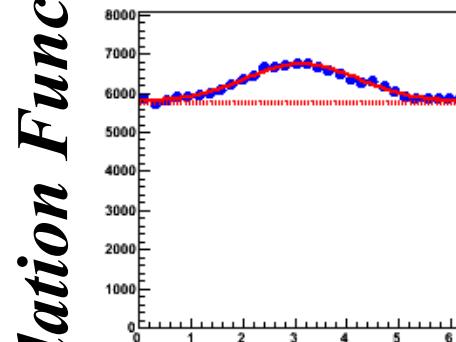
Correlation Function

$\langle p_T^a \rangle = 2.00 \text{ GeV}/c$

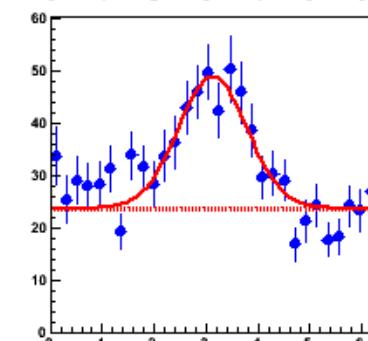
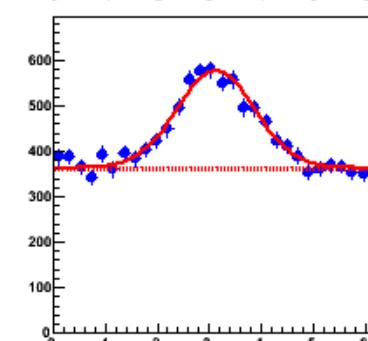
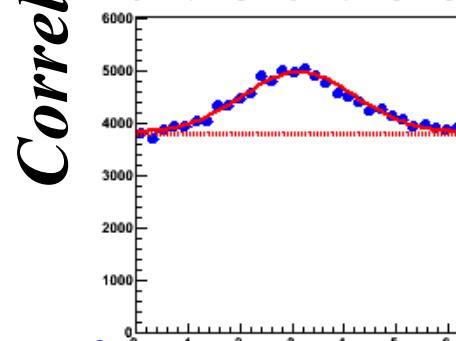
$\langle p_T^a \rangle = 3.10 \text{ GeV}/c$



dAu 0-20%



dAu 60-88%



p_T^t, π^0



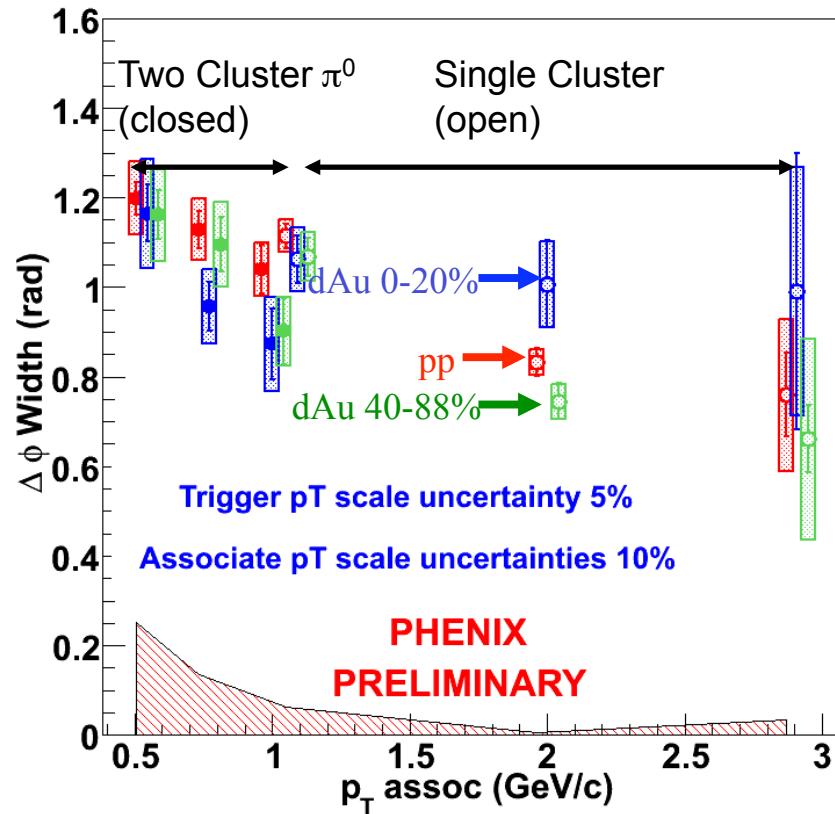
$\Delta\phi$



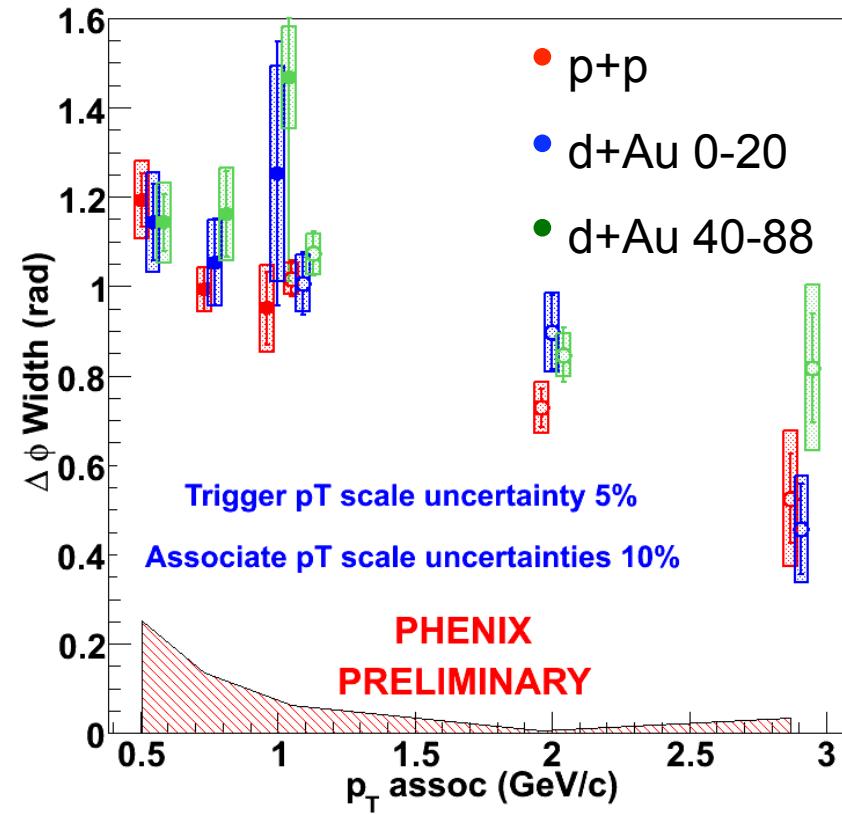
$\Delta\eta = 3.4$ Correlations: Widths

- No significant broadening between p+p and d+Au within large experimental uncertainties

Trigger π^0 : $|\eta| < 0.35$, $2.0 < p_T < 3.0 \text{ GeV}/c$

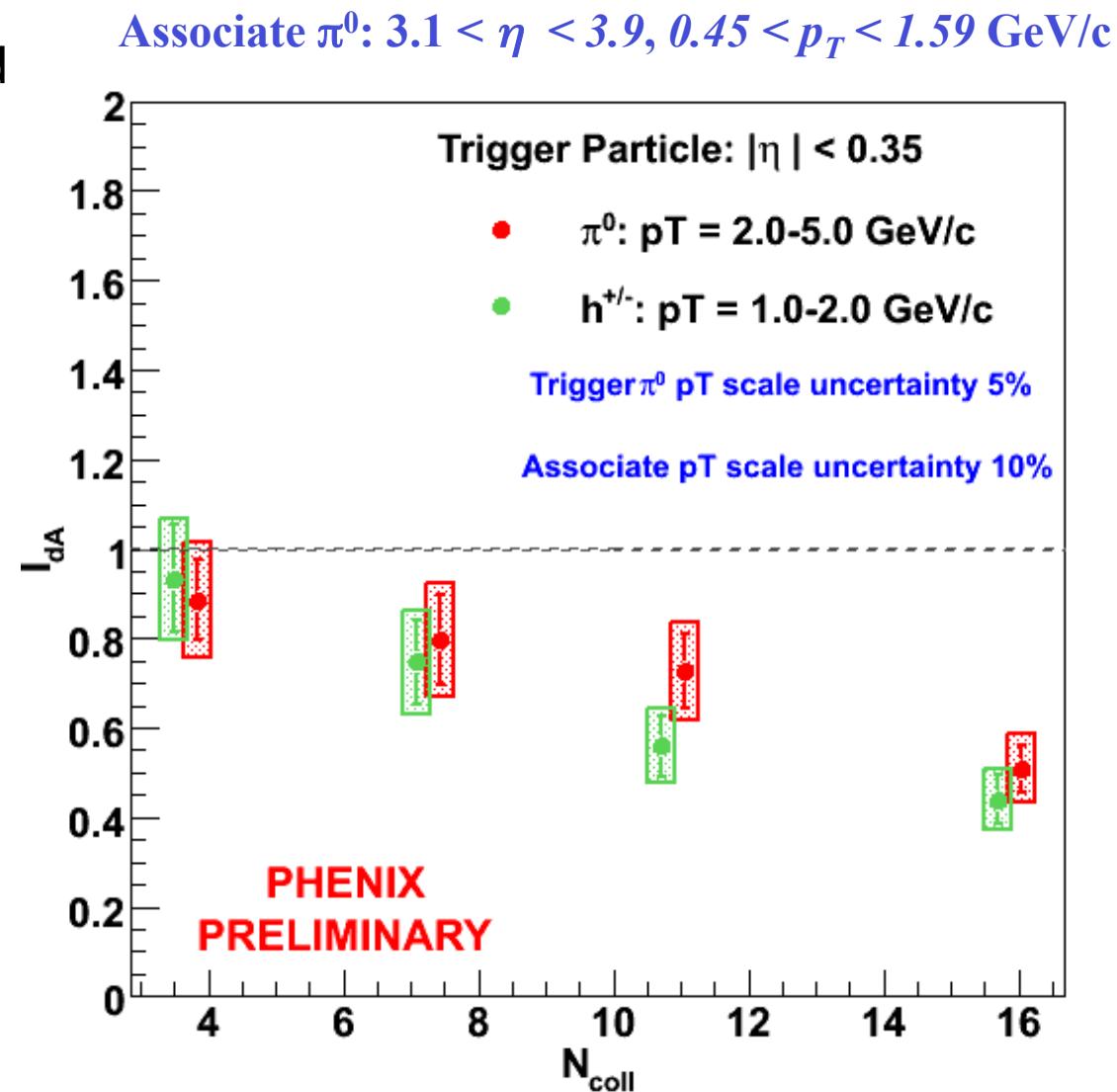


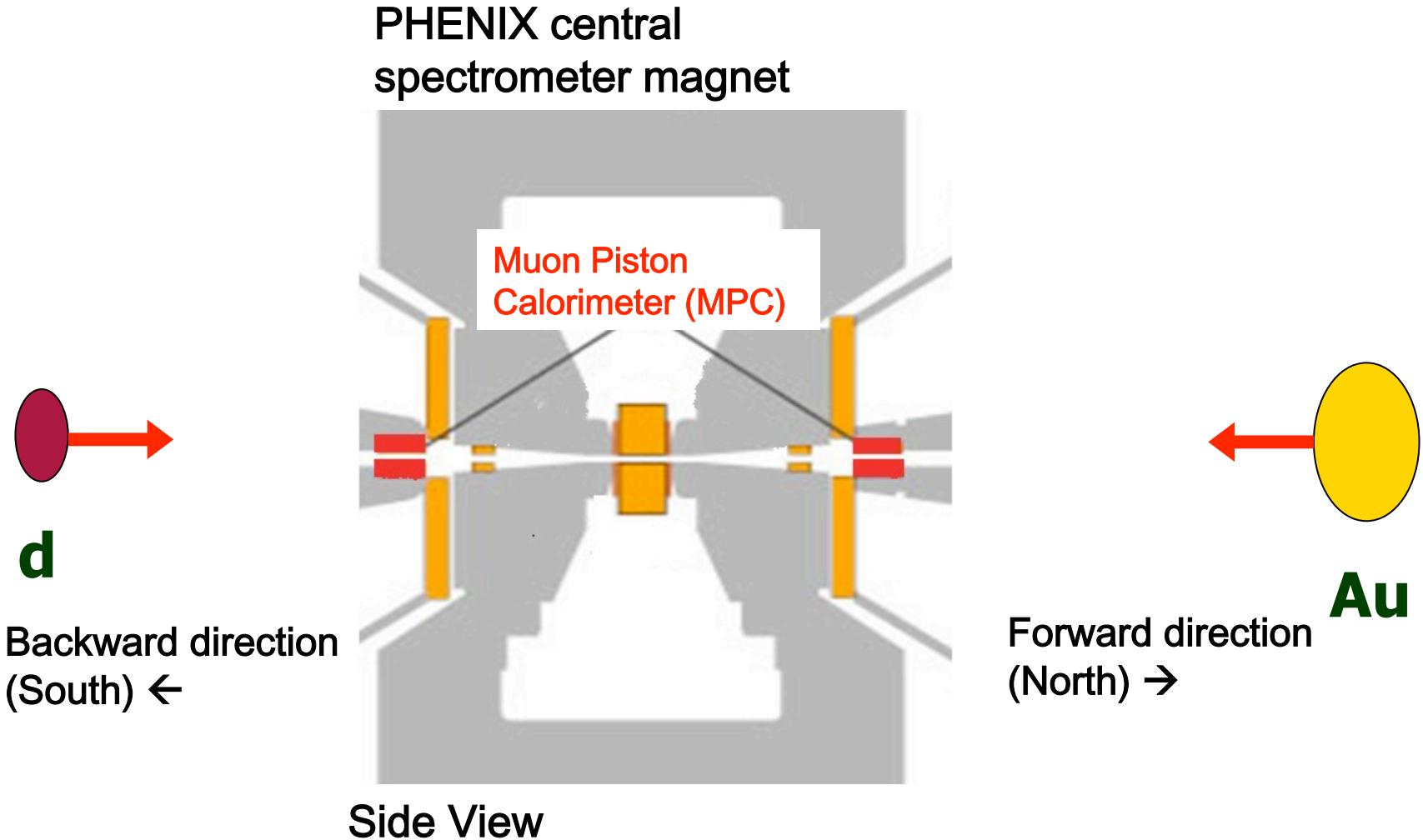
Trigger π^0 : $|\eta| < 0.35$, $3.0 < p_T < 5.0 \text{ GeV}/c$



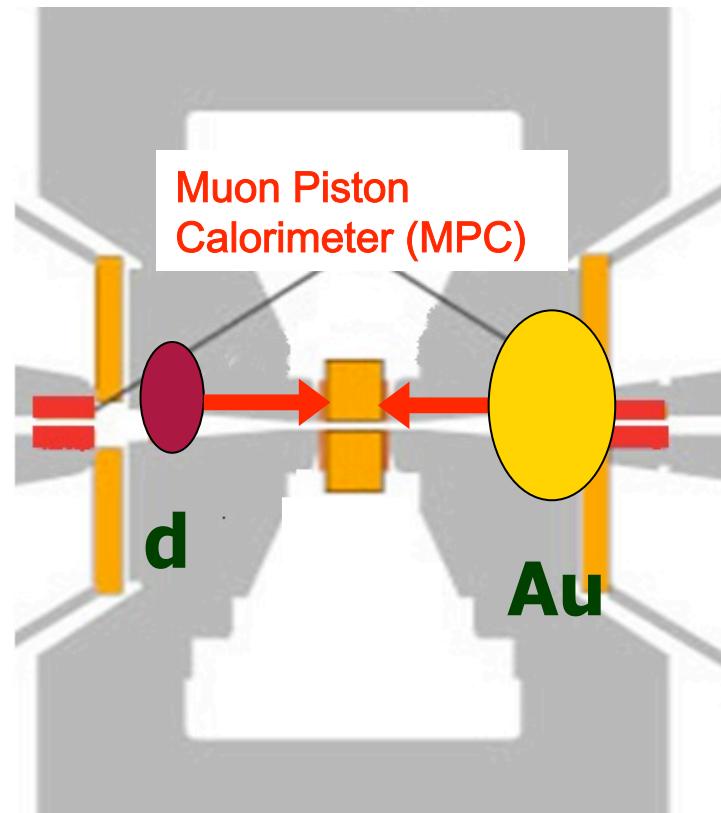
$\Delta\eta = 3.4$ Correlations: I_{dA}

- I_{dA} for central triggered events for reconstructed π^0
- Increasing suppression of I_{dA} reaches a factor 2 for central events
- Indicates di-jet suppression





PHENIX central
spectrometer magnet



Side View

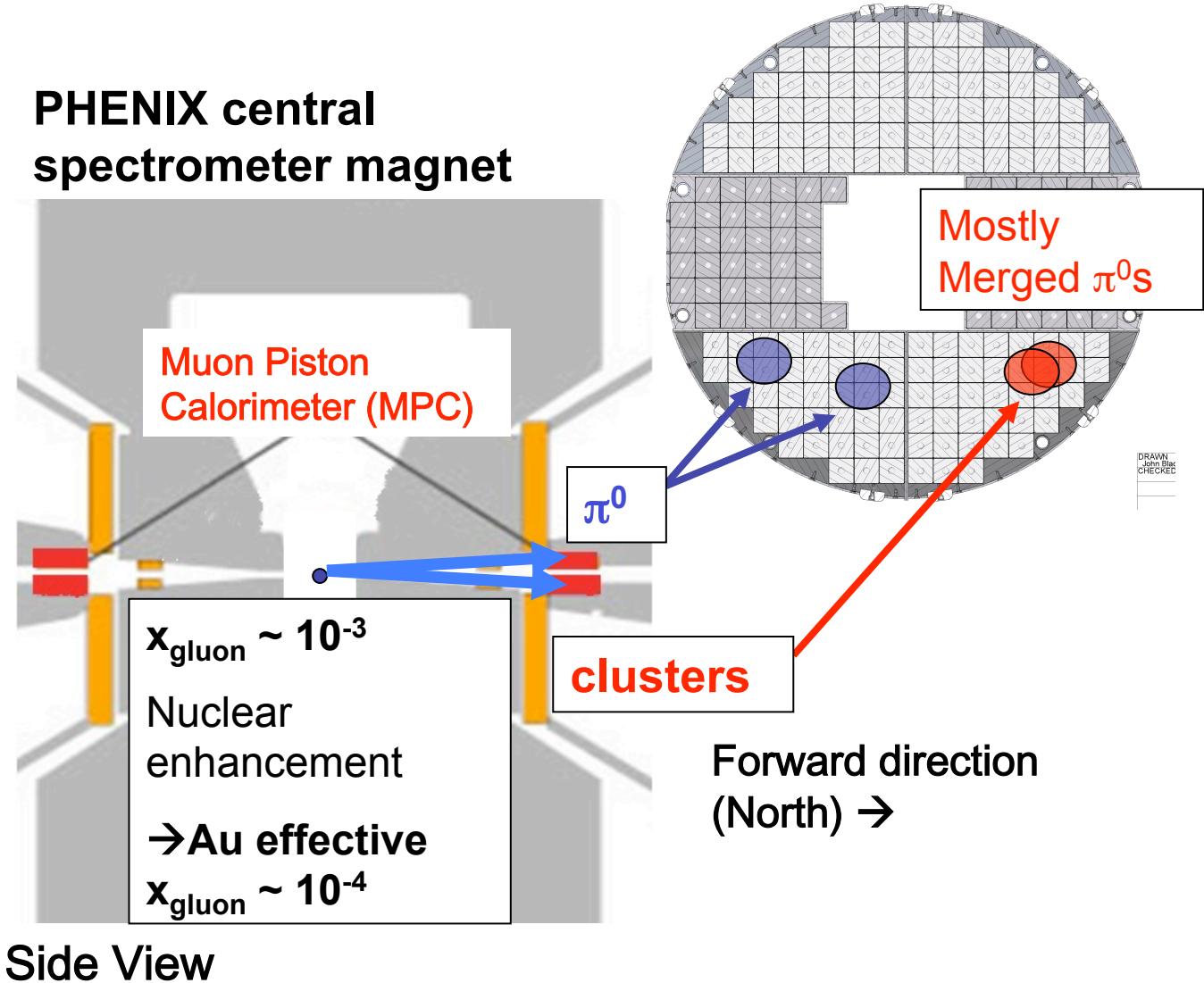


Forward Di-jet Signal with $\eta_{\text{trig}}, \eta_{\text{assoc}} = 3.4$



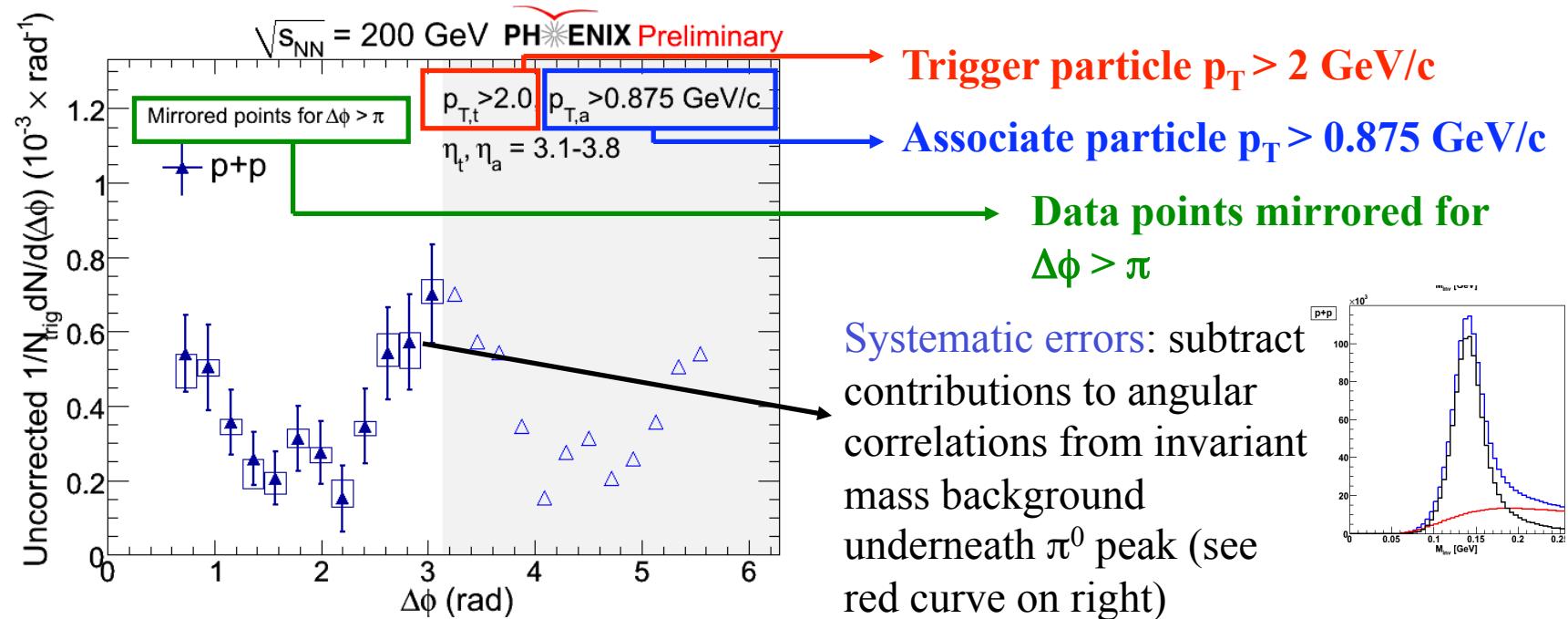
PHENIX central
spectrometer magnet

Backward direction
(South) ←

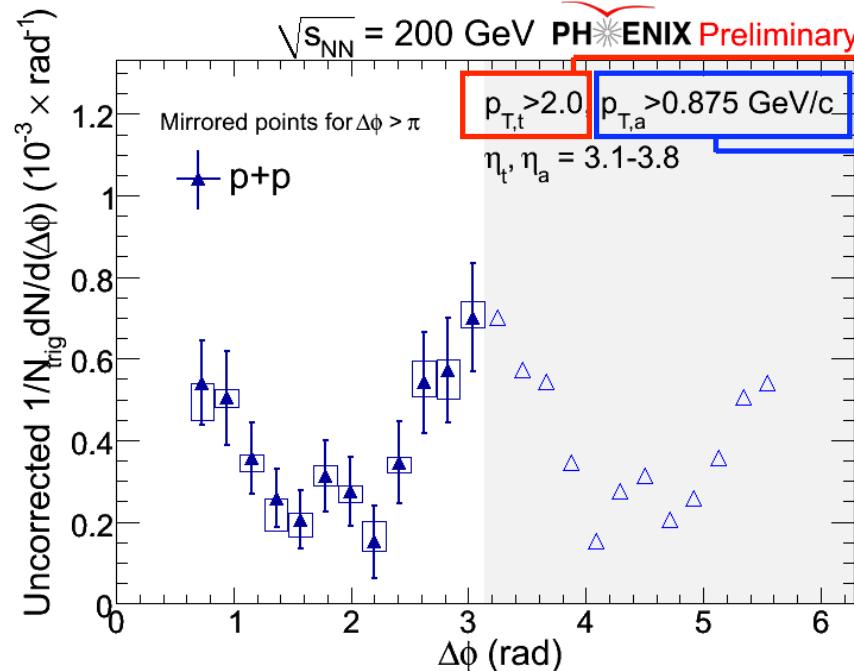


Forward/Forward Correlations: p+p

- Show per-trigger correlation functions, i.e. $1/N_{trig} dN/d(\Delta\phi)$
 - Area of away-side peak represents conditional yield without efficiency correction
 - More work needed to determine uncorrelated background level
 - Conditional yields, widths not shown

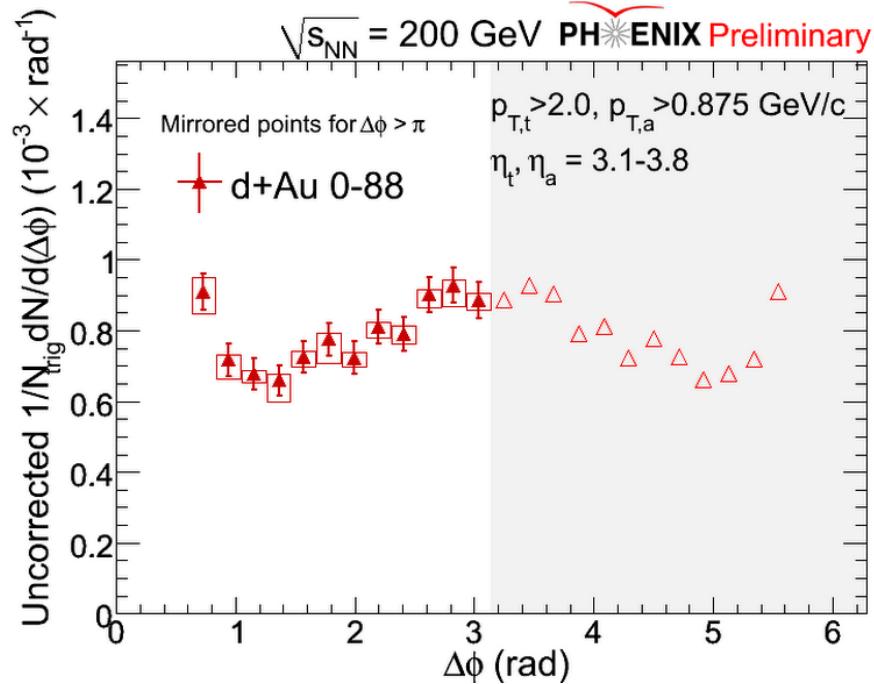


p+p vs d+Au MinBias

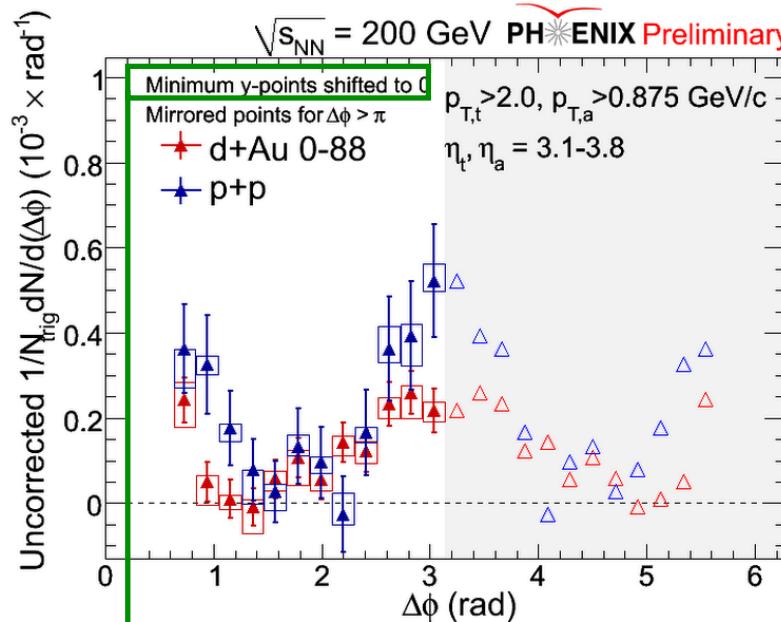
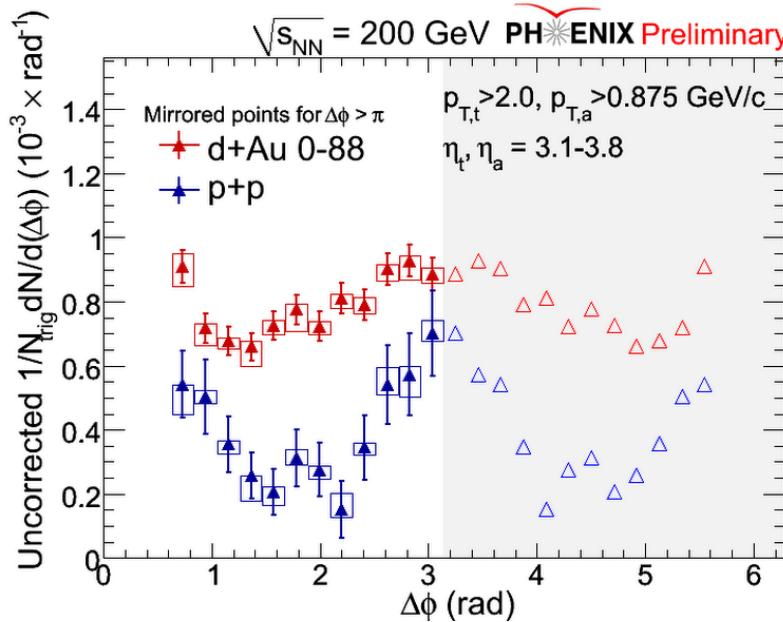


Trigger particle $p_T > 2 \text{ GeV}/c$
Associate particle $p_T > 0.875 \text{ GeV}/c$

Data qualitatively indicates angular decorrelation of d+Au compared to p+p



p+p vs d+Au MinBias (a closer look)



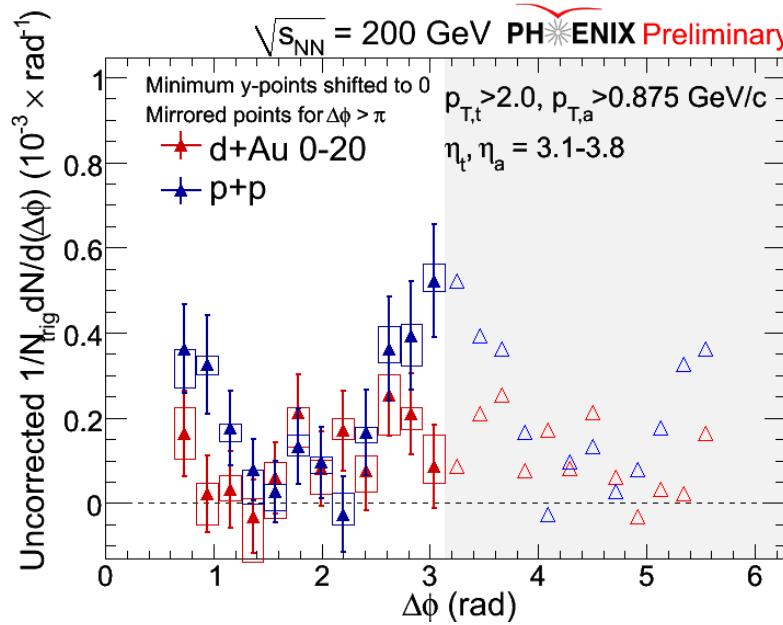
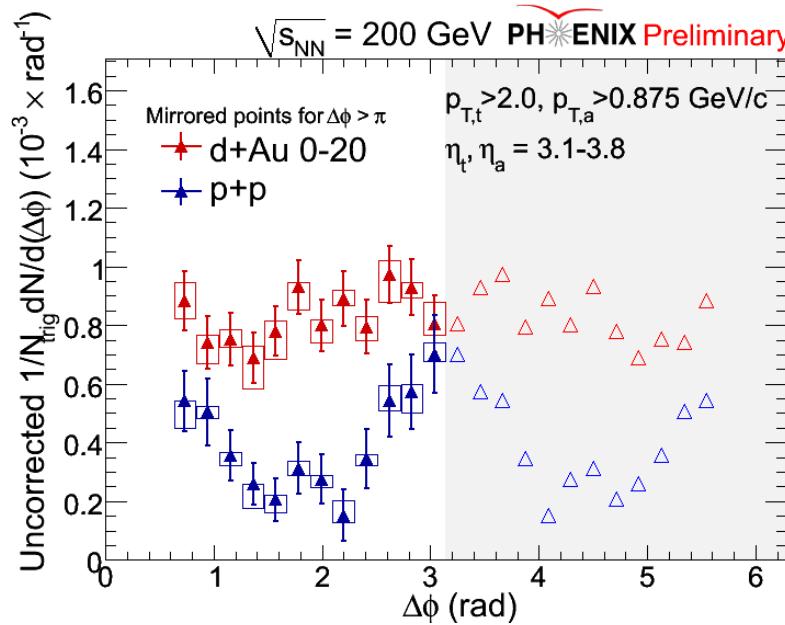
Data qualitatively indicates angular decorrelation of d+Au compared to p+p

Shift minimum y-values to 0 (for comparison only)

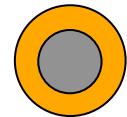
It also appears that there is a suppressed conditional yield in d+Au vs. p+p



p+p vs d+Au Central



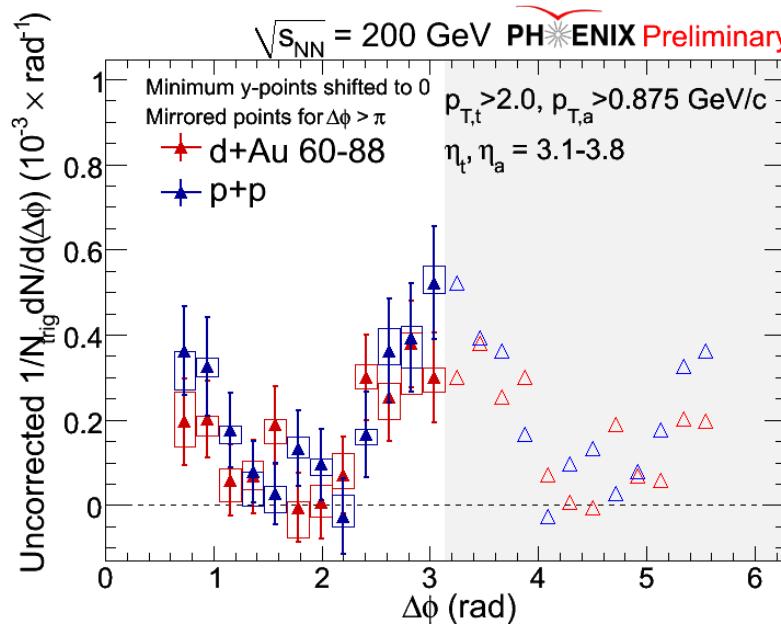
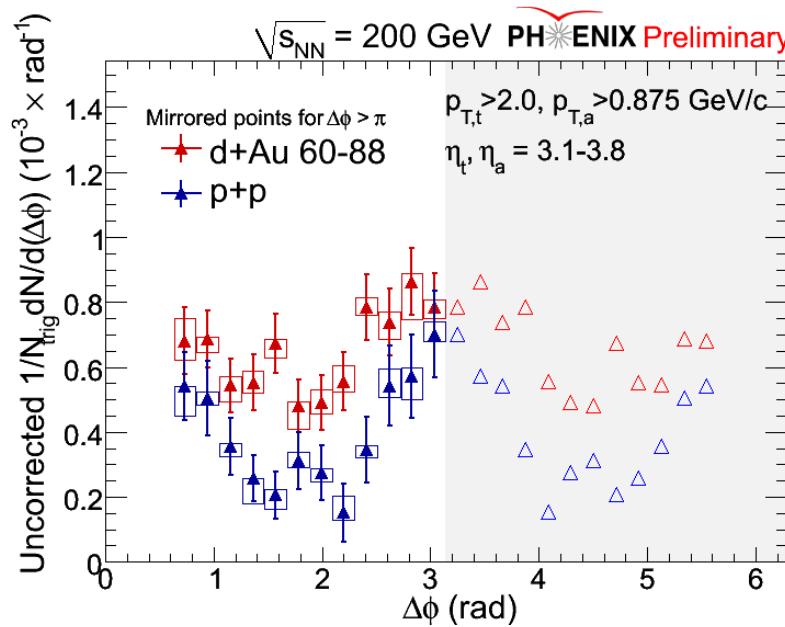
Decorrelation and/or suppression seem to get stronger for **central** d+Au collisions



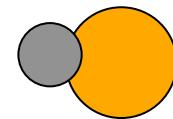
Beam view of d+Au central collision



p+p vs d+Au Peripheral



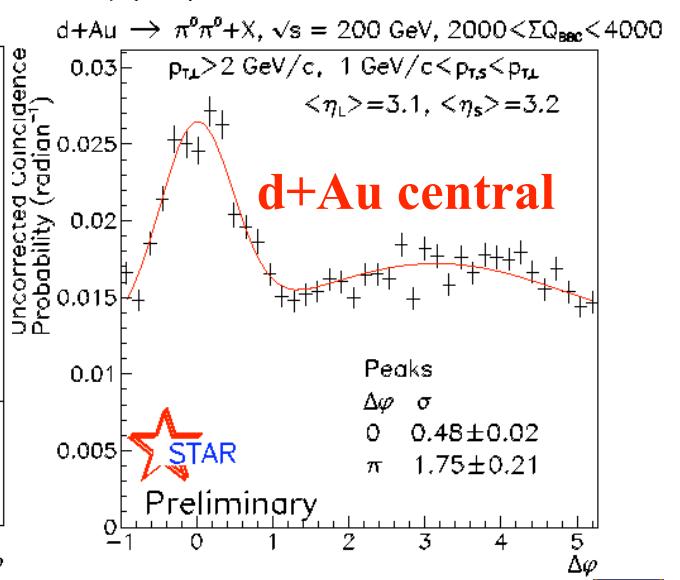
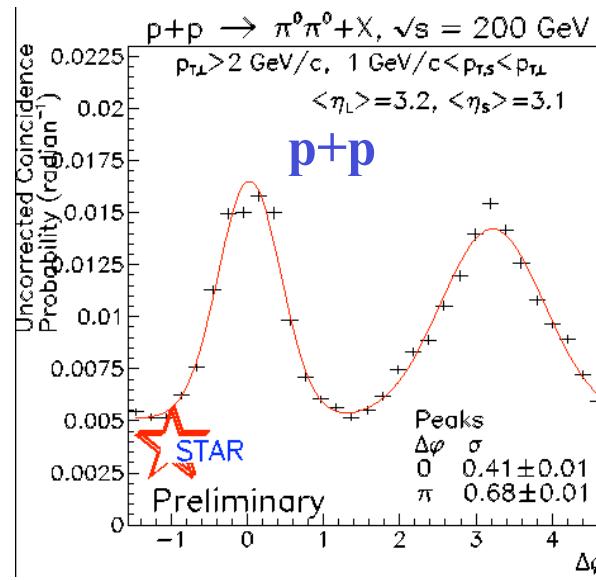
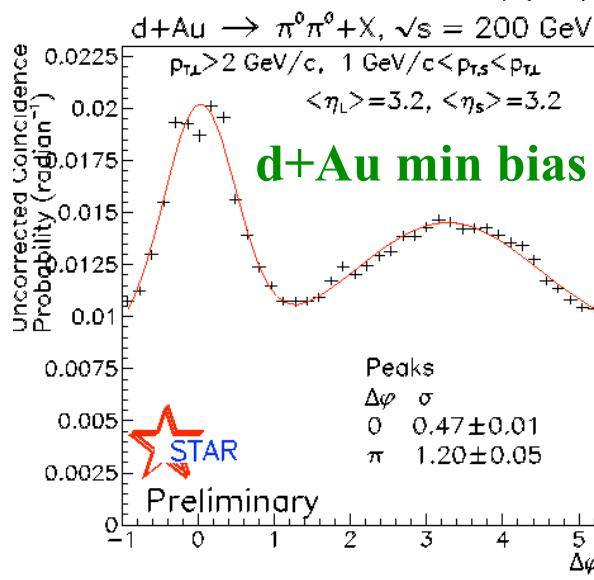
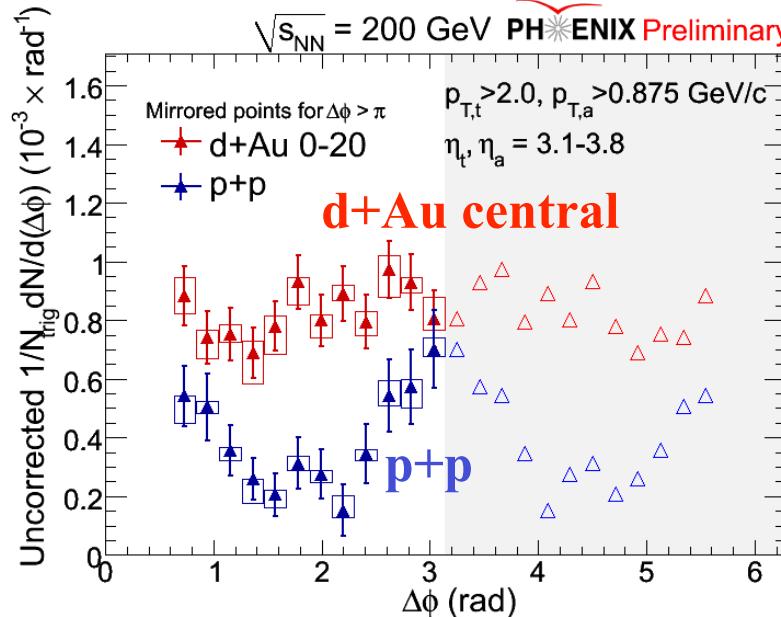
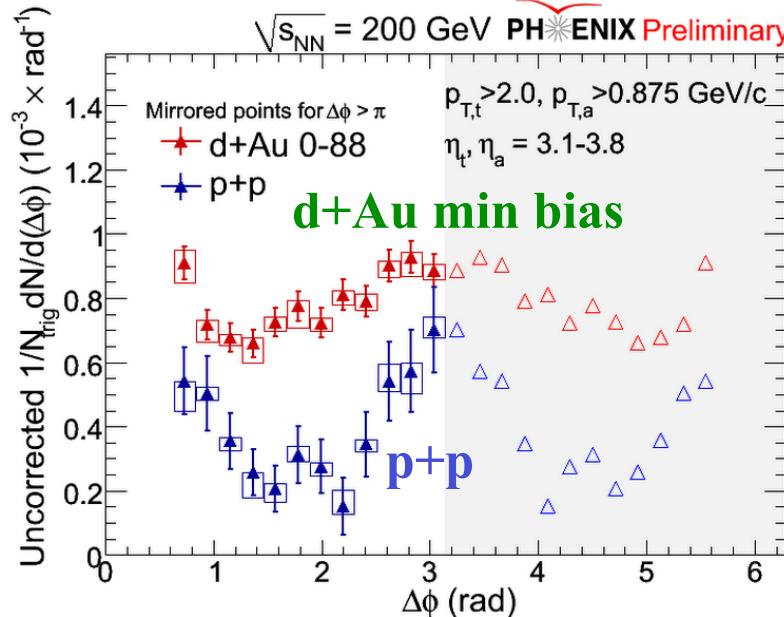
Peripheral d+Au collisions
are more similar to p+p
collisions



Beam view of d+Au
peripheral collision



Comparison to STAR Data



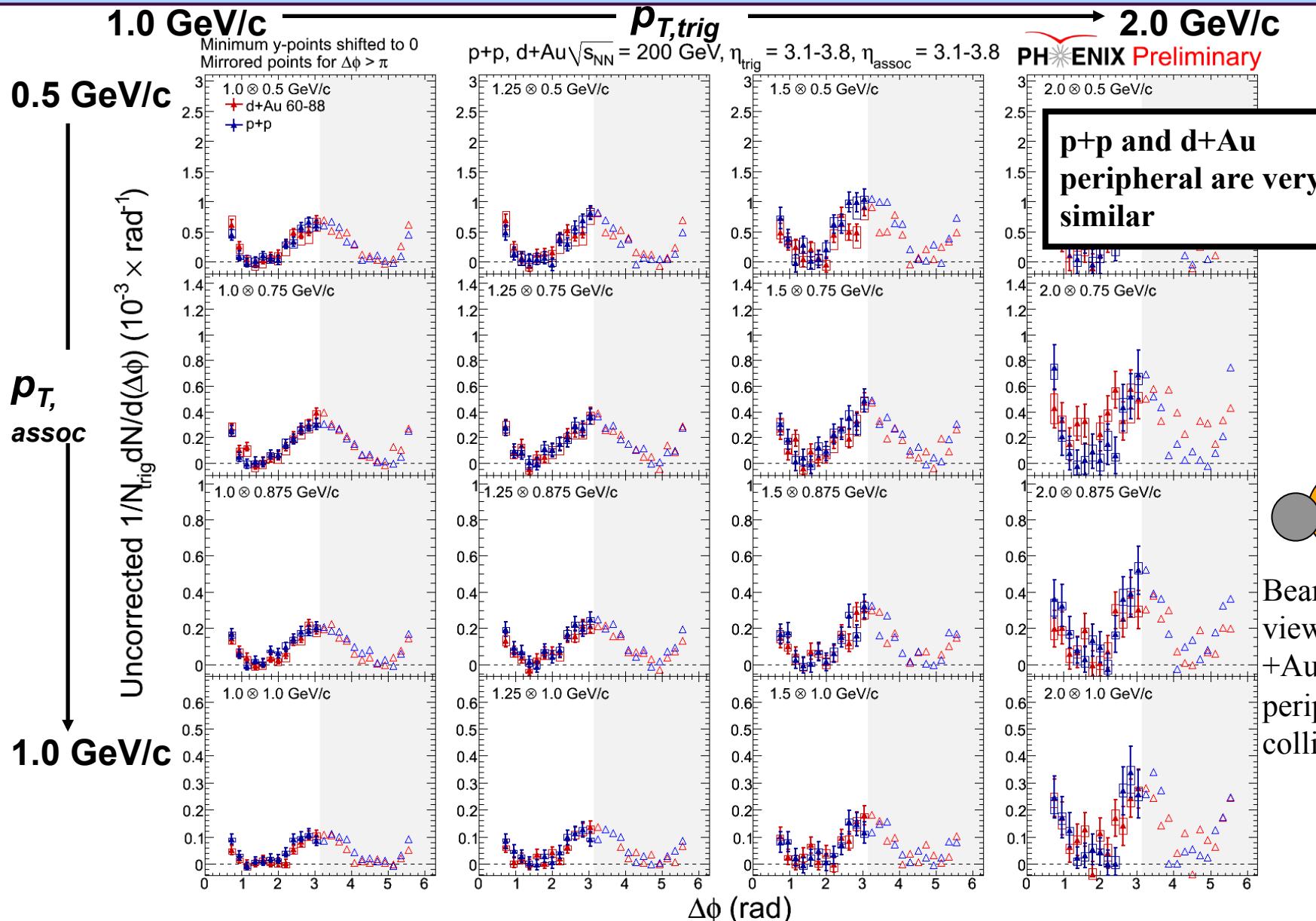
p_T Dependence

- Next, we show the p_T dependence of the correlation functions
 - $p_{T,\text{trig}} > 1.0 \text{ GeV}/c \rightarrow p_{T,\text{trig}} > 2.0 \text{ GeV}/c$
 - $p_{T,\text{assoc}} > 0.5 \text{ GeV}/c \rightarrow p_{T,\text{assoc}} > 1.0 \text{ GeV}/c$ (upper limit due to merging effects is set at 2 GeV/c, but varies with rapidity)
- The plots shown have the minimum y-points shifted to 0

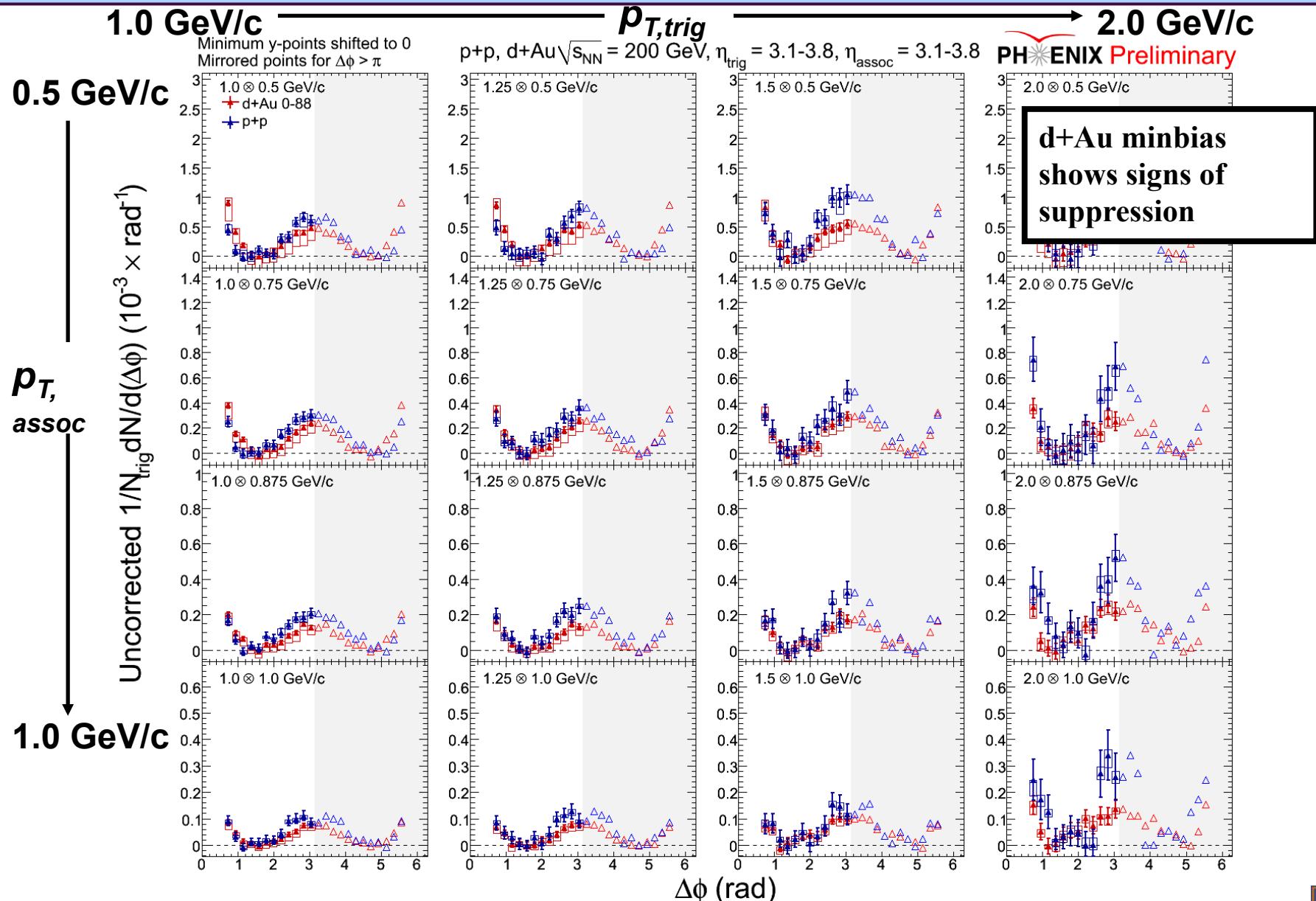


d+Au Peripheral, p+p Correlation Functions

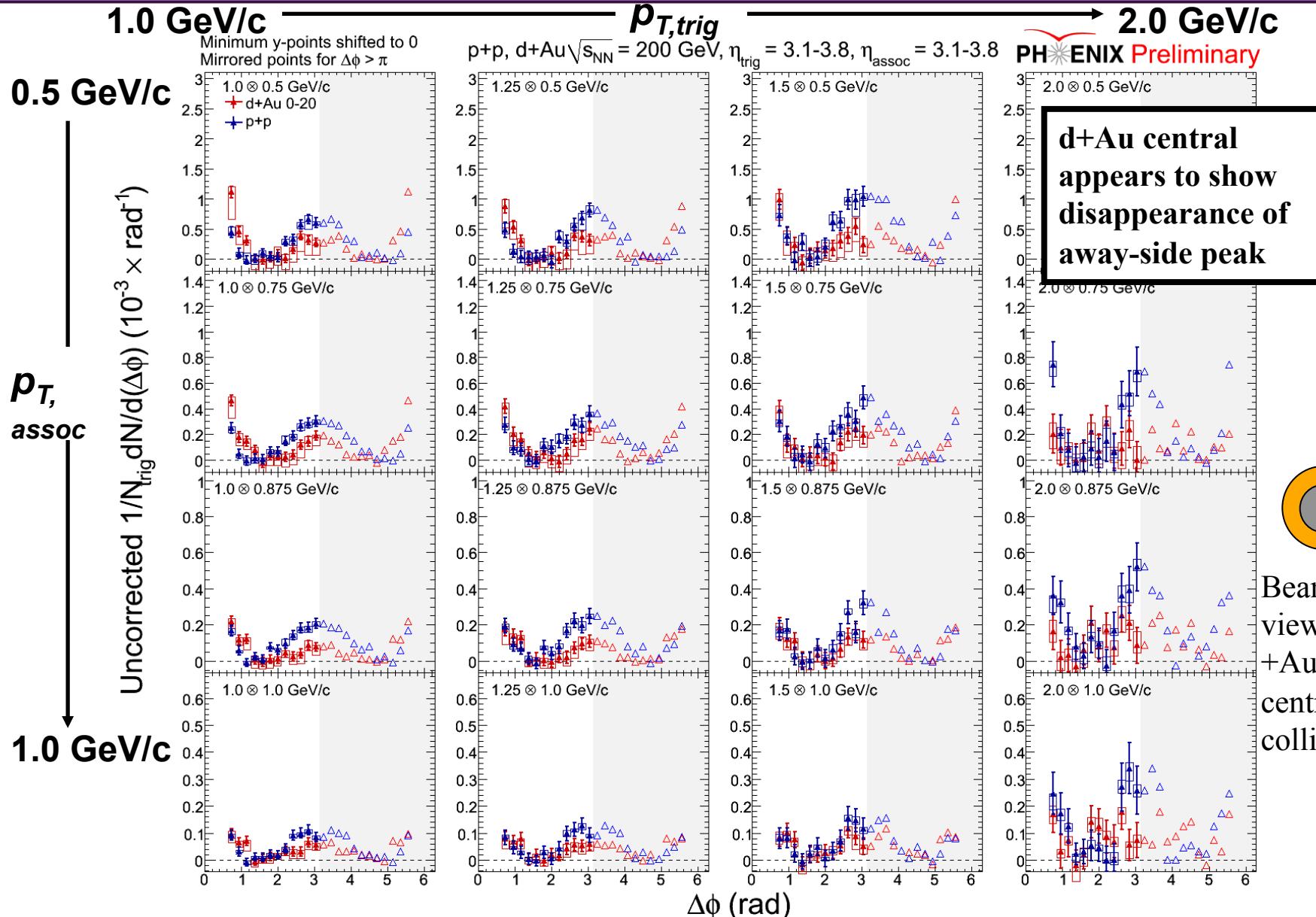
PHENIX



d+Au MinBias, p+p Correlation Functions



d+Au Central, p+p Correlation Functions



Summary & Outlook

■ Summary of Measurements

- Rapidity separated forward/central correlations ($\Delta\eta = 3.4$; trigger particle is at central rapidities)
 - No significant broadening between d+Au vs pp within experimental precision
 - Suppression of I_{dA} is observed as one goes to more central collisions, indicating di-jet suppression
- Forward/forward correlations ($\eta_{\text{trig,assoc}} = 3.1\text{-}3.8$)
 - Data seems qualitatively consistent with gluon saturation hypothesis that the d+Au yields are suppressed relative to p+p
 - Some of the data also suggest that the widths in d+Au are broadened
 - Need more work on uncorrelated background before making quantitative statements

■ Future Plans

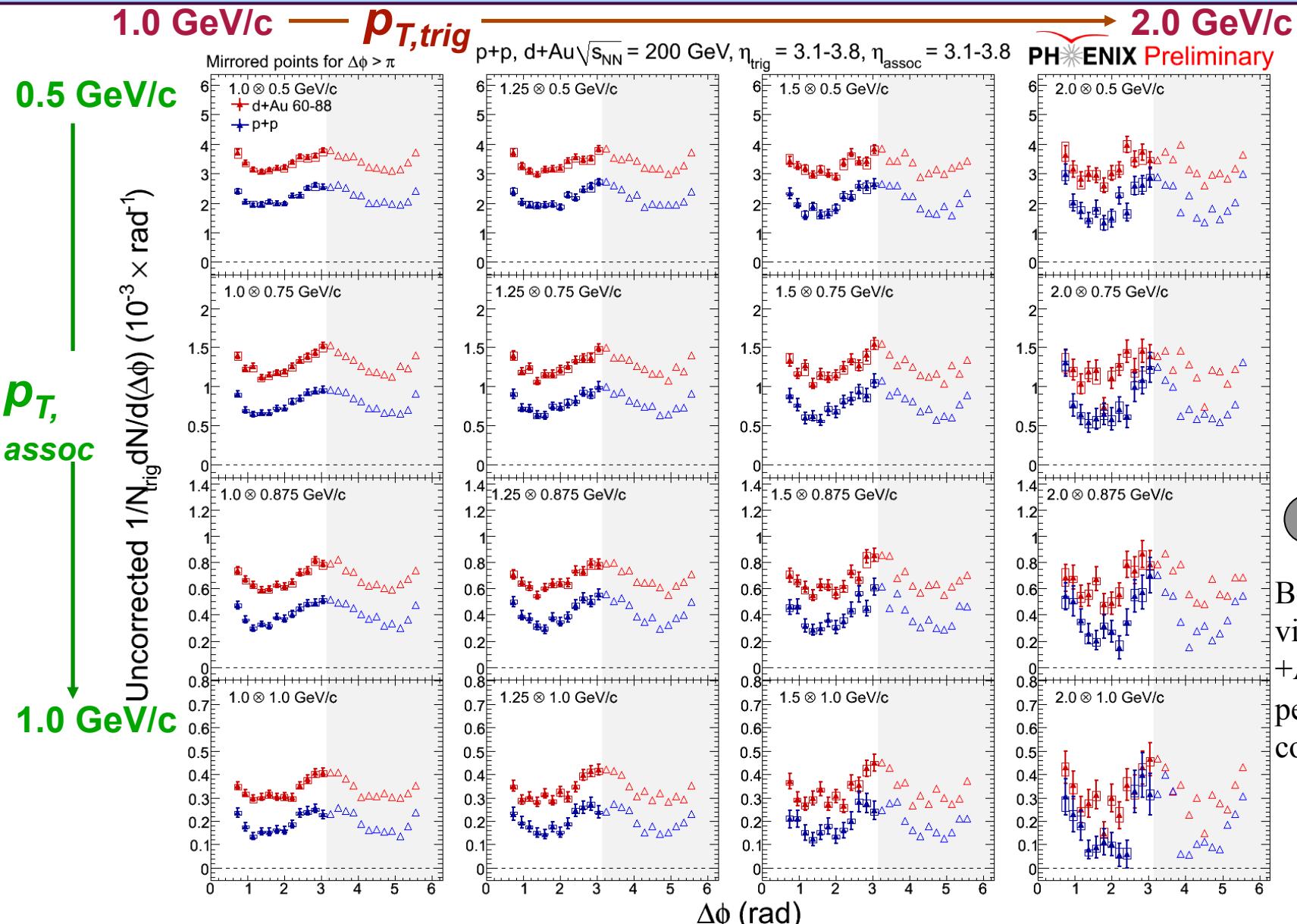
- Determine background, widths, and yields in forward/forward correlations
- Apply acceptance x efficiency correction



Backup Slides

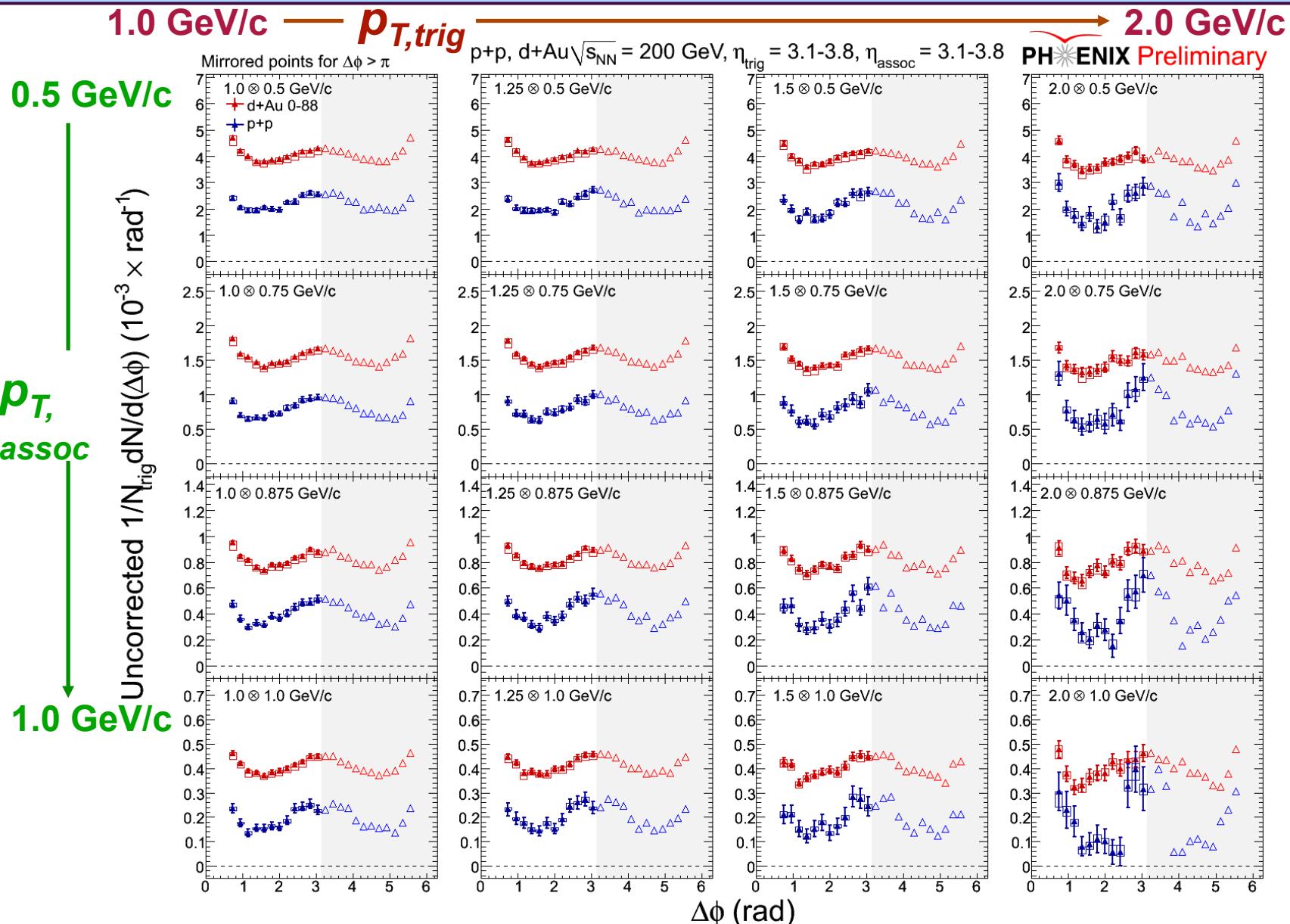


d+Au Peripheral, p+p Correlation Functions



d+Au MinBias, p+p Correlation Functions

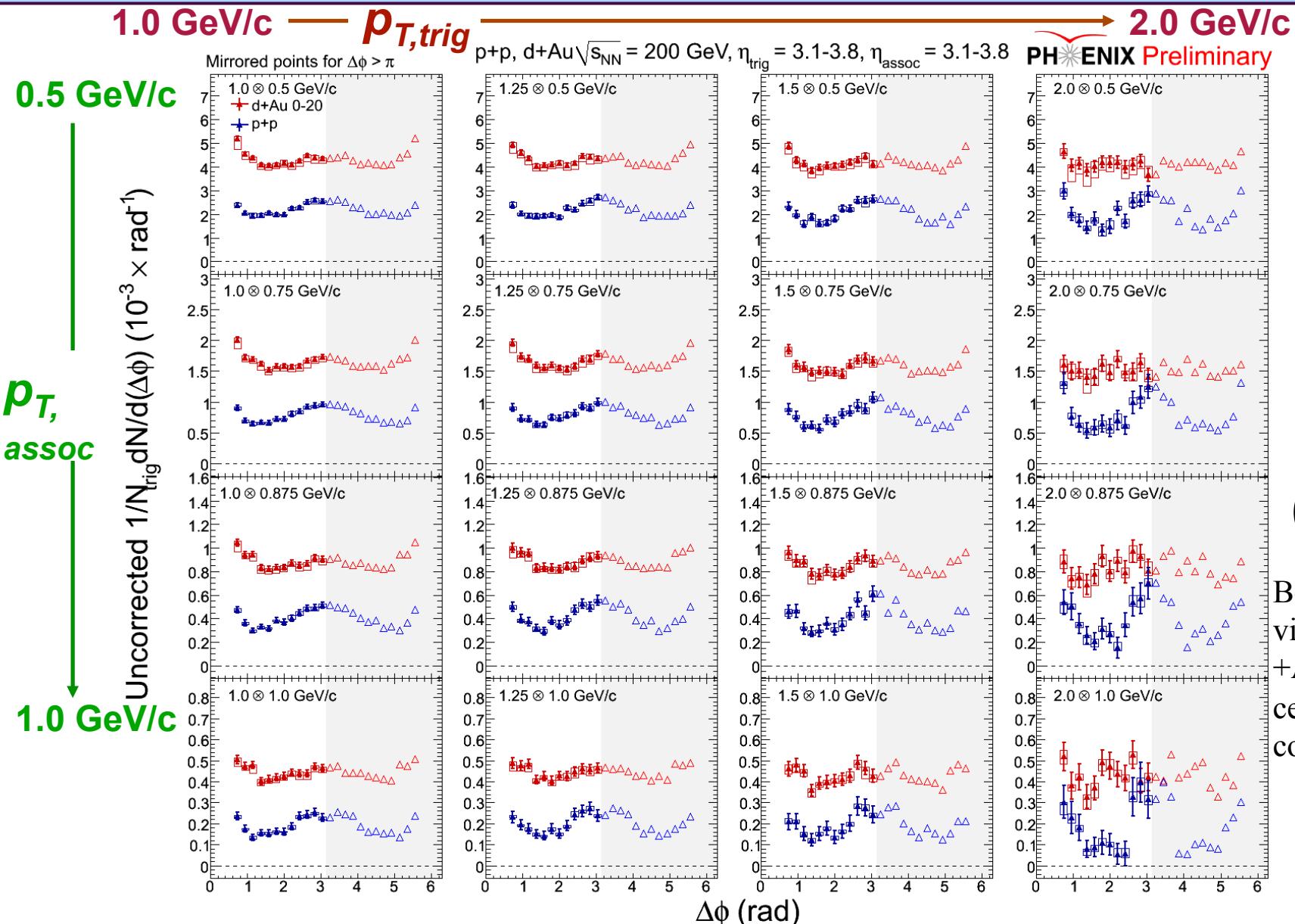
PHENIX



Forward $\Delta\phi$ Di-Hadron Correlations in PHENIX



d+Au Central, p+p Correlation Functions



I_{dA} vs J_{dA}: Can we decouple effects?

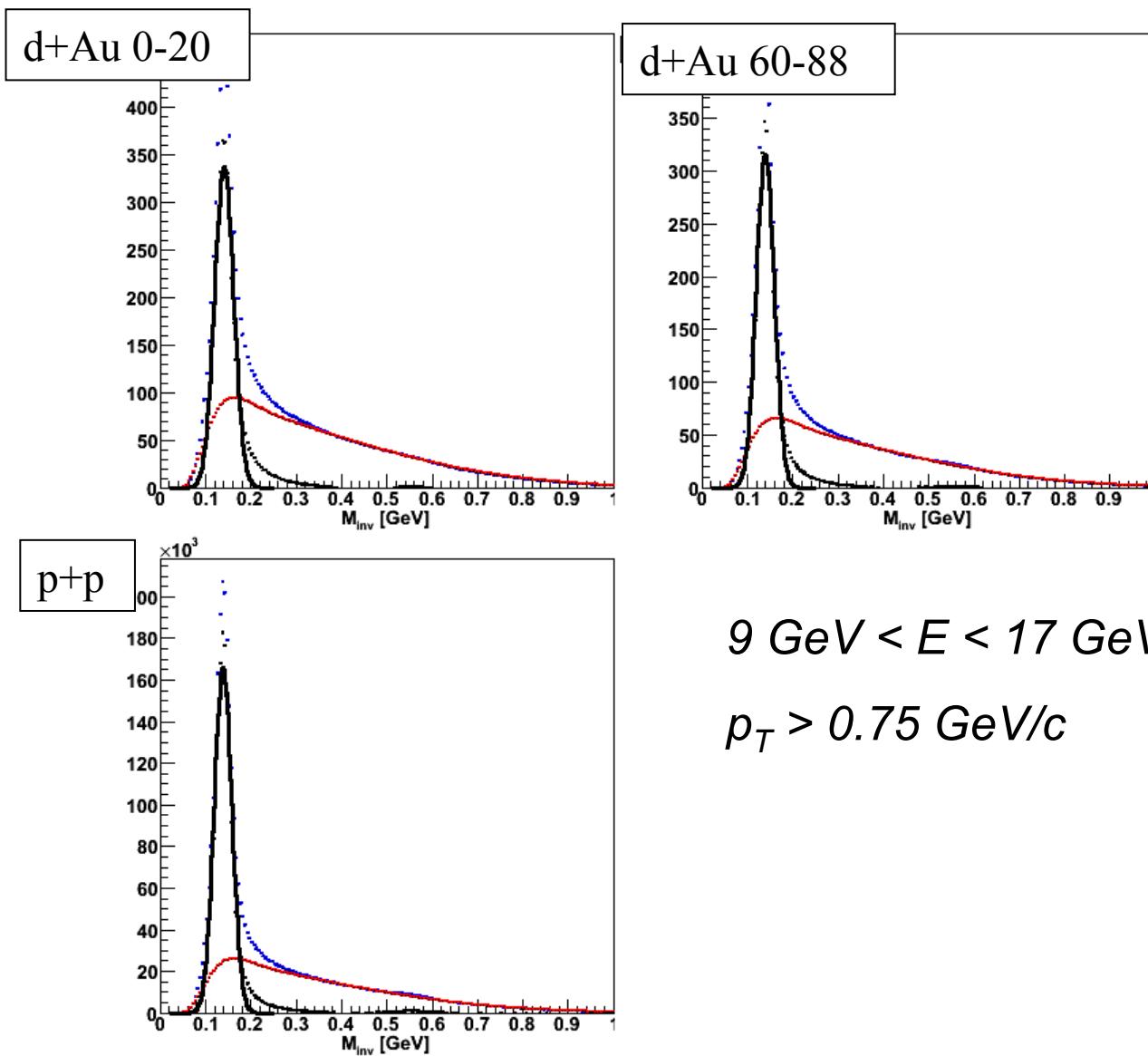
$$I_{dA} = \frac{1}{R_{dA}} \times J_{dA}$$

$$I_{dA} = \frac{\frac{1}{N_{trig}^{dA}} \frac{dN_{assoc}^{dA}}{d\Delta\phi}}{\frac{1}{N_{trig}^{pp}} \frac{dN_{assoc}^{pp}}{d\Delta\phi}} = \frac{\frac{\langle N_{coll} \rangle N_{trig}^{pp}}{N_{evt}^{pp}}}{\frac{N_{trig}^{dA}}{N_{evt}^{dA}}} \times \frac{\frac{1}{N_{evt}^{dA}} \frac{dN_{(assoc|trig)}^{dA}}{d\Delta\phi}}{\langle N_{coll} \rangle \frac{1}{N_{evt}^{pp}} \frac{dN_{(assoc|trig)}^{pp}}{d\Delta\phi}}$$

- I_{dA} is the per trigger comparison of d+Au jet associated counts relative to p+p
- J_{dA} is the rate of the associated pairs from a jet (per minbias event)
- Can we use this to tell if the jets are modified, or do they disappear?
- From the CNT-MPC correlations, we get I_{dA} ~ 0.5, and R_{dA} ~ 1.1
 - J_{dA} ~ 0.5
 - The rate of correlated pairs is about half of p+p
 - Does this imply that the missing jets have disappeared, and not that they are modified, since I_{dA} ~ J_{dA}?
 - But not true for STAR FMS triggered-central barrel, where I_{dA} ~ 1 and J_{dA} ~ 0.5



MPC Invariant Mass Peaks



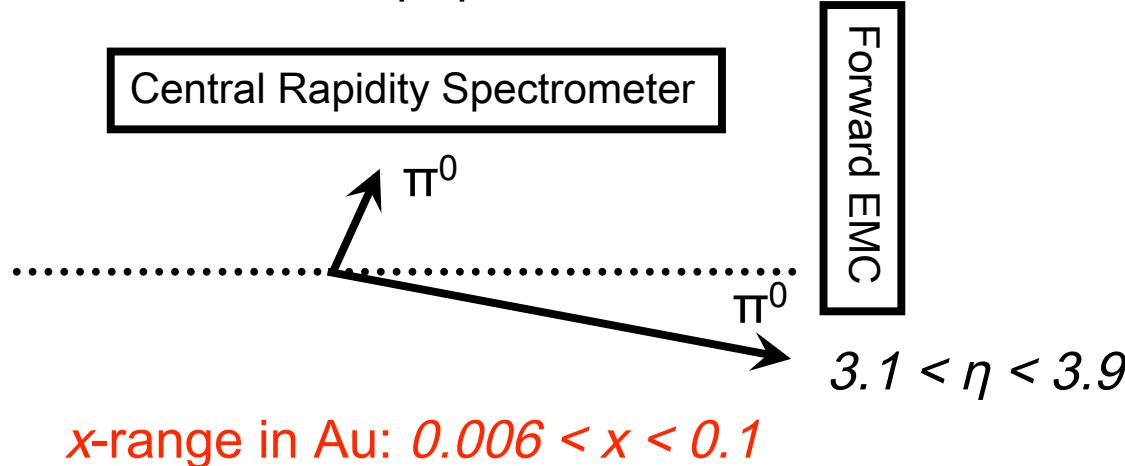
$9 \text{ GeV} < E < 17 \text{ GeV}$

$p_T > 0.75 \text{ GeV}/c$



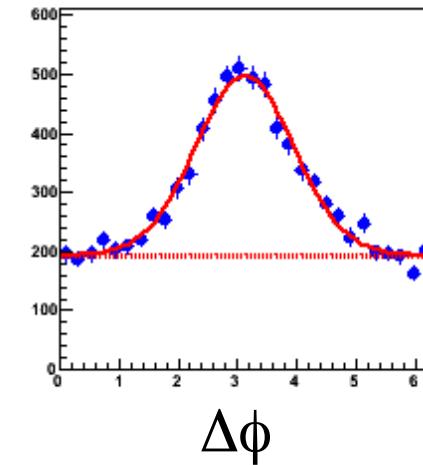
Experimental Method: Overview

- Using azimuthal angle (transverse direction) two-particle correlations
 - d+Au ($L_{\text{int}} = 80 \text{ nb}^{-1}$), pp ($L_{\text{int}} = 5.2 \text{ pb}^{-1}$) collisions at $\sqrt{s}_{NN} = 200 \text{ GeV}$ from RHIC Run8
 - Trigger particles are $(\pi^0, h^{+/-})$ with $|\eta| < 0.35$
 - Associate particles are **forward** π^0 s and clusters with $3.1 < \eta < 3.9$
 - Probes gluon distribution at moderately low x
- Signal of saturation is suppression/broadening of away-side peak in d +Au relative to p+p

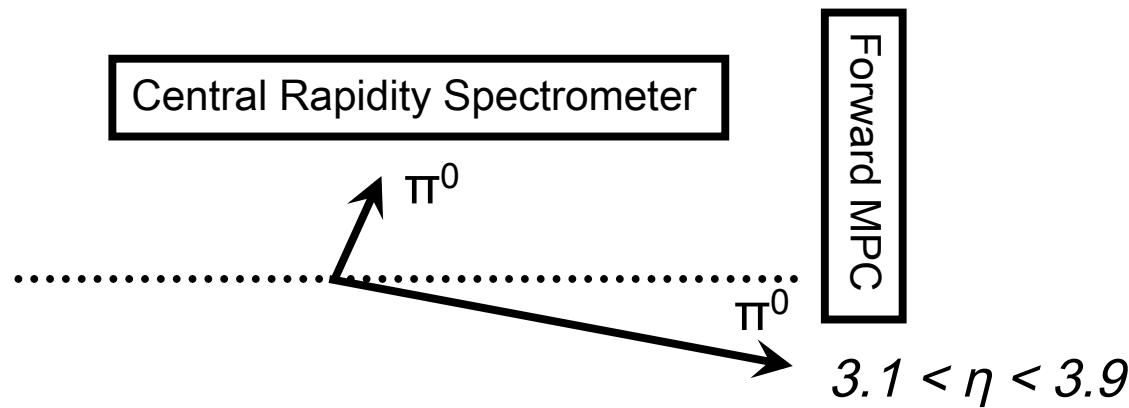


From calculation by Marco Stratmann

Example Correlation Function
for rapidity separated particles



Correlation Functions for central arm/MPC



π^0 (trigger,central)/ π^0 (associate,forward)

$2.0 < p_T^t < 3.0 \text{ GeV}/c$

for all plots

pp

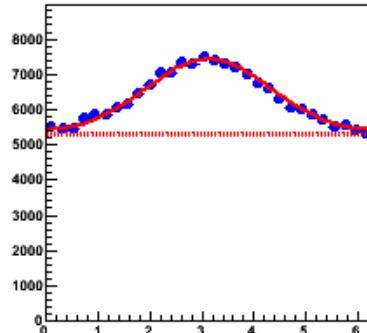
dAu 0-20%

dAu 60-88%

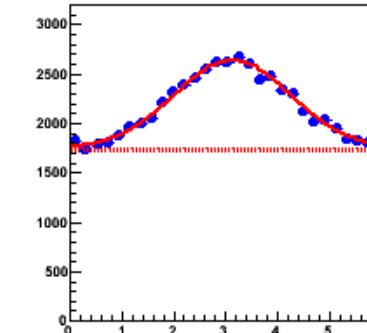
p_T^t, π^0

Correlation Function

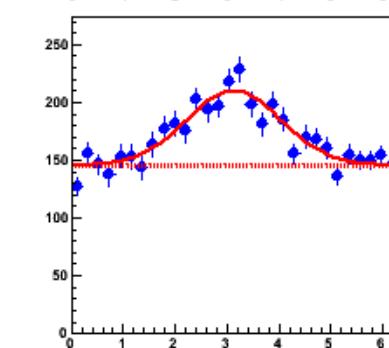
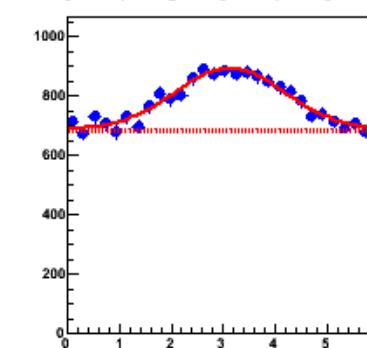
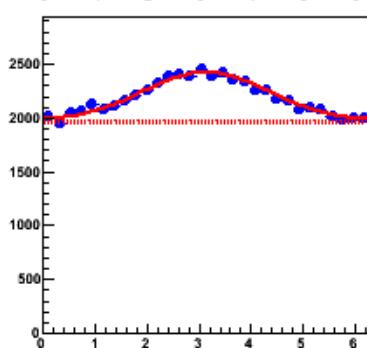
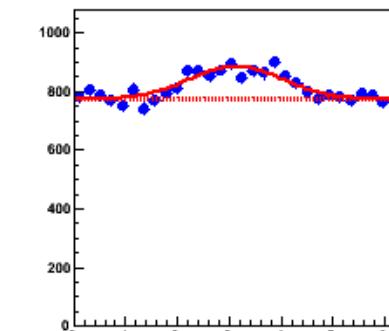
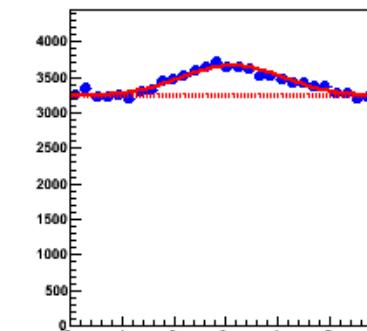
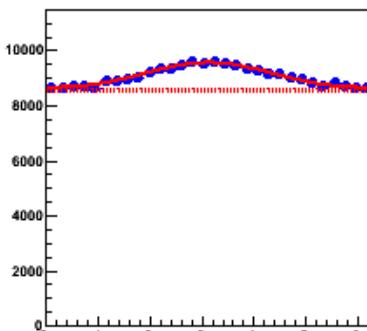
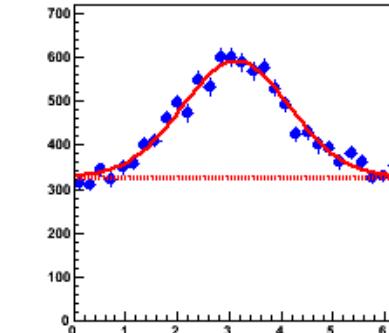
$\langle p_T^a \rangle = 0.55 \text{ GeV}/c$



$\langle p_T^a \rangle = 0.77 \text{ GeV}/c$



$\langle p_T^a \rangle = 1.00 \text{ GeV}/c$



$\Delta\phi$

Forward $\Delta\phi$ Di-Hadron Correlations in PHENIX

46



π^0 (trigger,central)/ π^0 (associate,forward)

$3.0 < p_T^t < 5.0 \text{ GeV}/c$

for all plots

pp

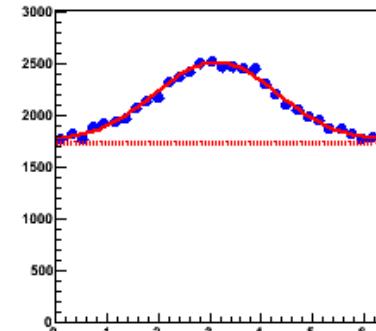
dAu 0-20%

dAu 60-88%

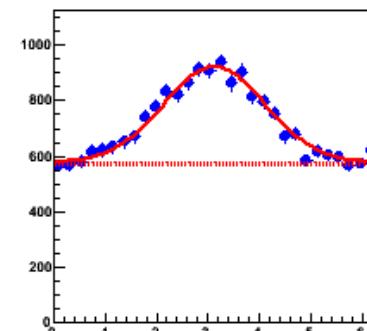
p_T^t, π^0

Correlation Function

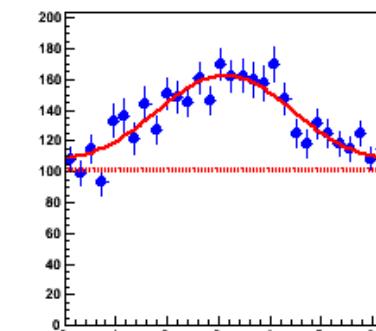
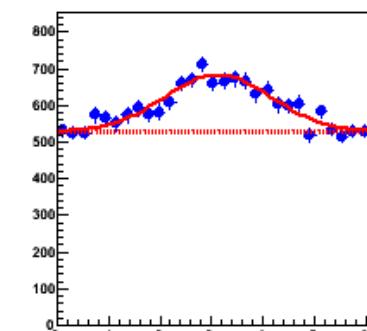
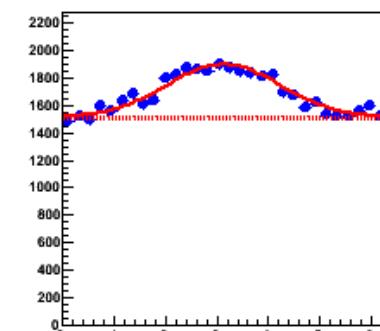
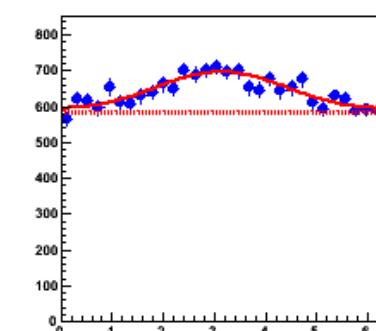
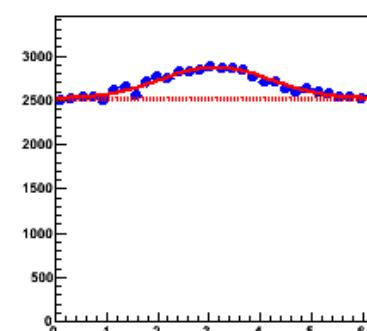
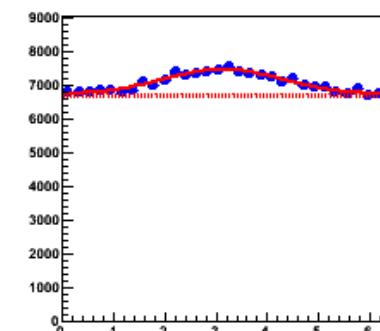
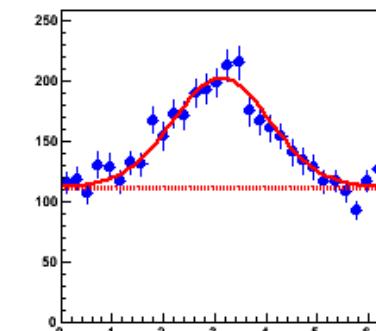
$\langle p_T^a \rangle = 0.55 \text{ GeV}/c$



$\langle p_T^a \rangle = 0.77 \text{ GeV}/c$



$\langle p_T^a \rangle = 1.00 \text{ GeV}/c$



Forward $\Delta\phi$ Di-Hadron Correlations in PHENIX

$\Delta\phi$



$h^{+/-}$ (trigger,central)/ π^0 (associate,forward)

$1.0 < p_T^t < 2.0 \text{ GeV}/c$

for all plots

pp

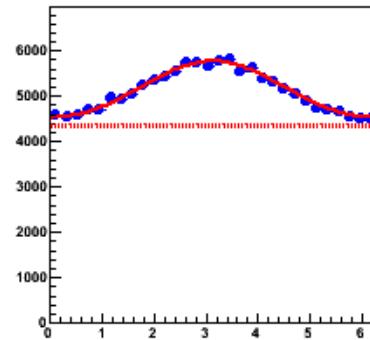
dAu 0-20%

dAu 60-88%

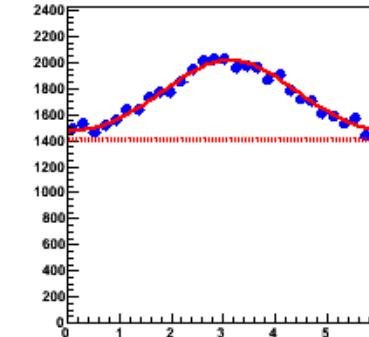
$p_T^t, h^{+/-}$

Correlation Function

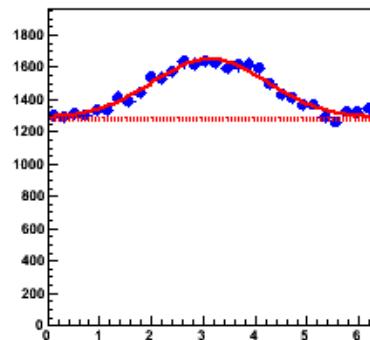
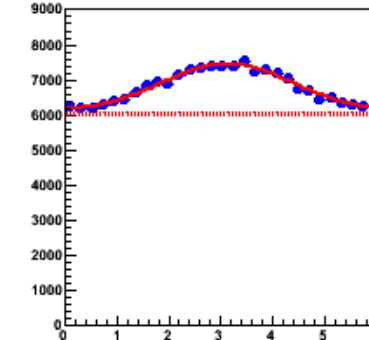
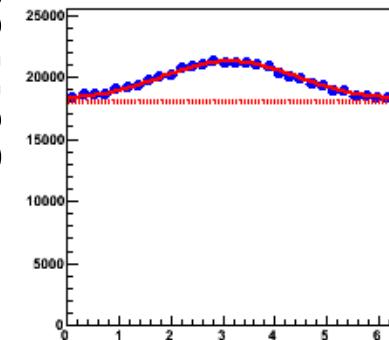
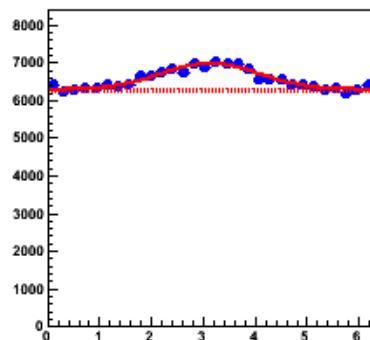
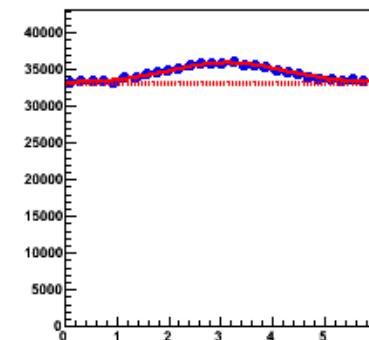
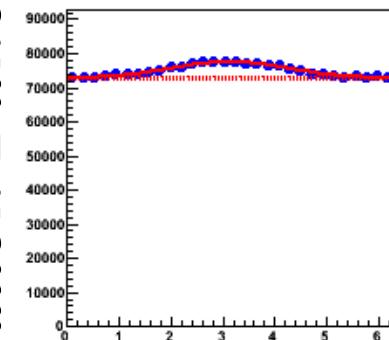
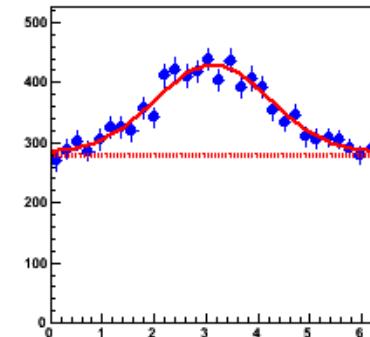
$\langle p_T^a \rangle = 0.55 \text{ GeV}/c$



$\langle p_T^a \rangle = 0.77 \text{ GeV}/c$



$\langle p_T^a \rangle = 1.00 \text{ GeV}/c$



Forward $\Delta\phi$ Di-Hadron Correlations in PHENIX

$\Delta\phi$

48



π^0 (trigger,central)/cluster (associate,forward)

$2.0 < p_T^t < 3.0 \text{ GeV}/c$

for all plots

pp

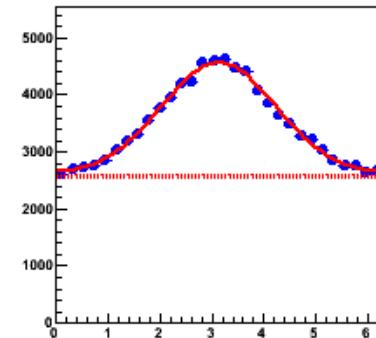
dAu 0-20%

dAu 60-88%

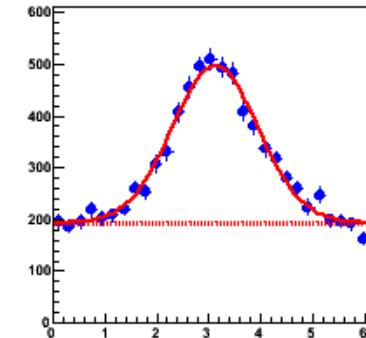
p_T^t, π^0

Correlation Function

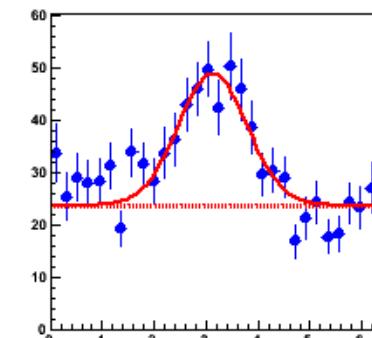
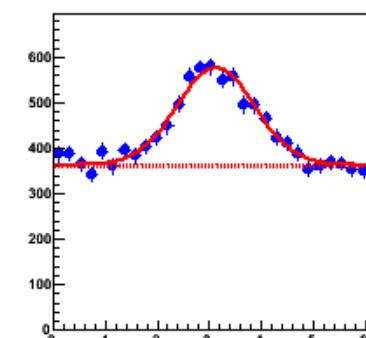
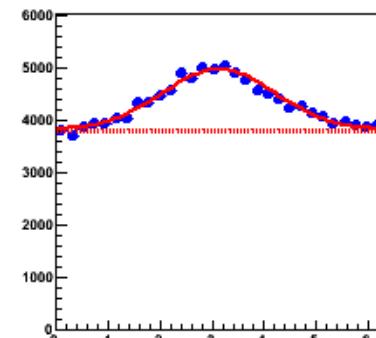
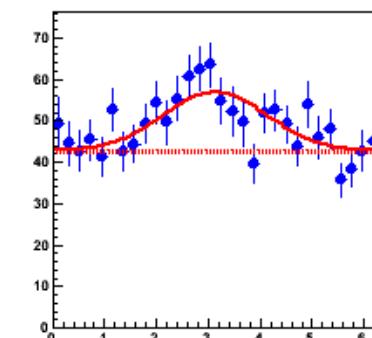
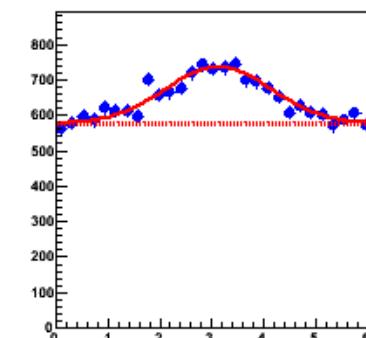
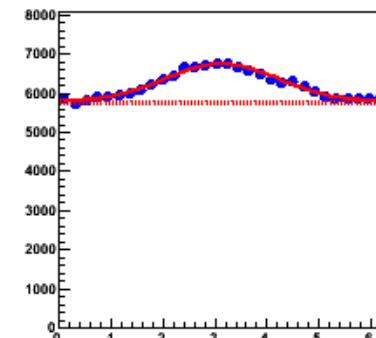
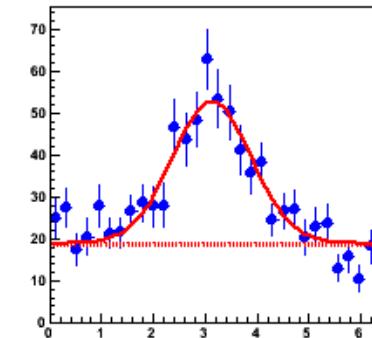
$\langle p_T^a \rangle = 1.09 \text{ GeV}/c$



$\langle p_T^a \rangle = 2.00 \text{ GeV}/c$



$\langle p_T^a \rangle = 3.10 \text{ GeV}/c$



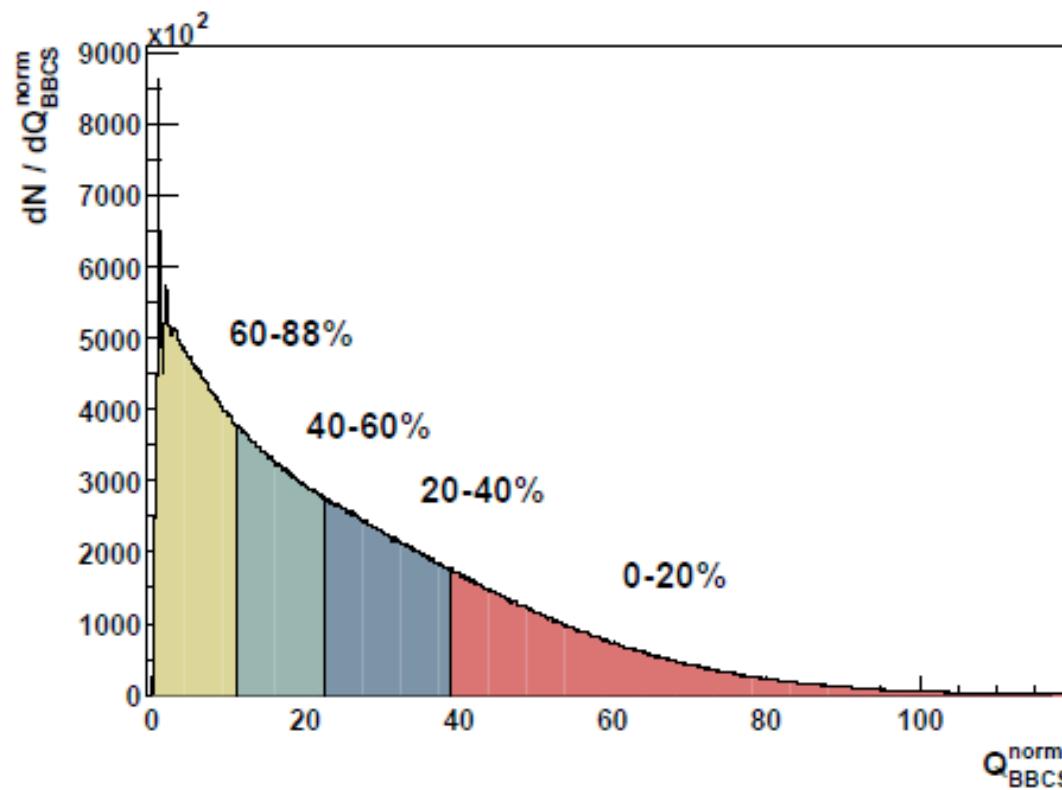
$p_T^a, \text{cluster}$

$\Delta\phi$

Forward $\Delta\phi$ Di-Hadron Correlations in PHENIX

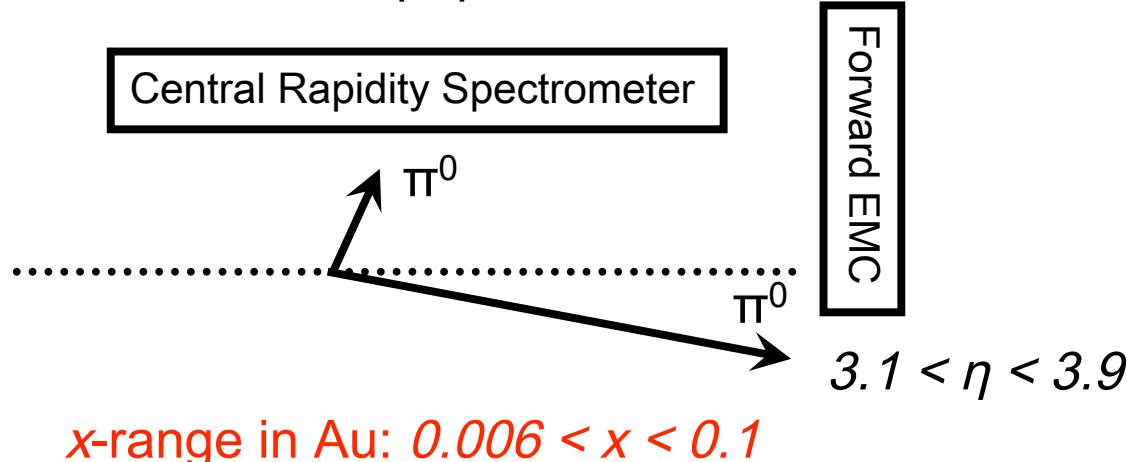


Centrality Determination in d+Au



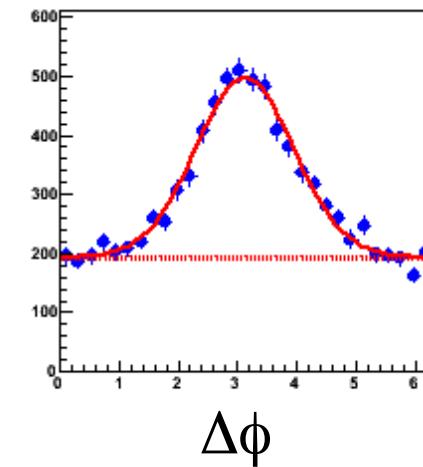
Azimuthal Angular Correlations

- Using azimuthal angle (transverse direction) two-particle correlations
 - d+Au ($L_{\text{int}} = 80 \text{ nb}^{-1}$), pp ($L_{\text{int}} = 5.2 \text{ pb}^{-1}$) collisions at $\sqrt{s}_{NN} = 200 \text{ GeV}$ from RHIC Run8
 - Trigger particles are $(\pi^0, h^{+/-})$ with $|\eta| < 0.35$
 - Associate particles are **forward** π^0 s and clusters with $3.1 < \eta < 3.9$
 - Probes gluon distribution at moderately low x
- Signal of saturation is suppression/broadening of away-side peak in d +Au relative to p+p



From calculation by Marco Stratmann

Example Correlation Function
for rapidity separated particles



PHENIX Muon Piston Calorimeter

Technology → ALICE(PHOS)

PbWO₄
avalanche photo diode readout

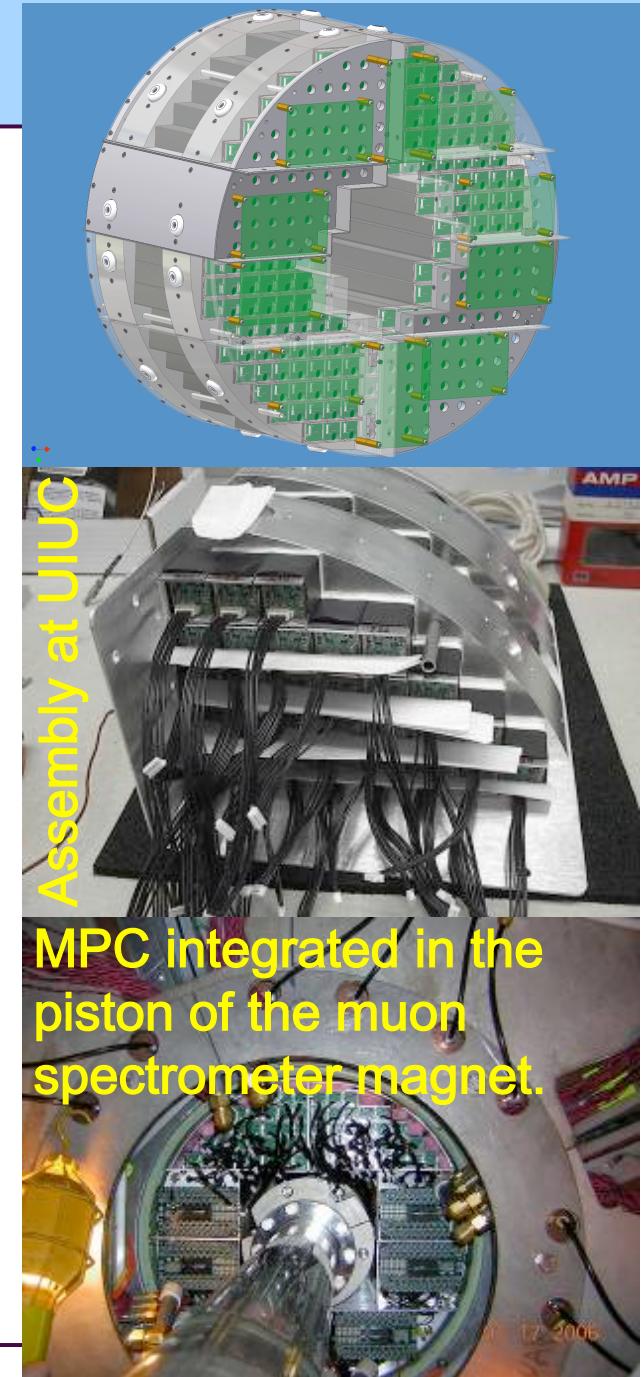
Acceptance:

$$3.1 < \eta < 3.9, \quad 0 < \varphi < 2\pi \\ -3.7 < \eta < -3.1, \quad 0 < \varphi < 2\pi$$

Both detectors were installed for 2008 d-Au run.

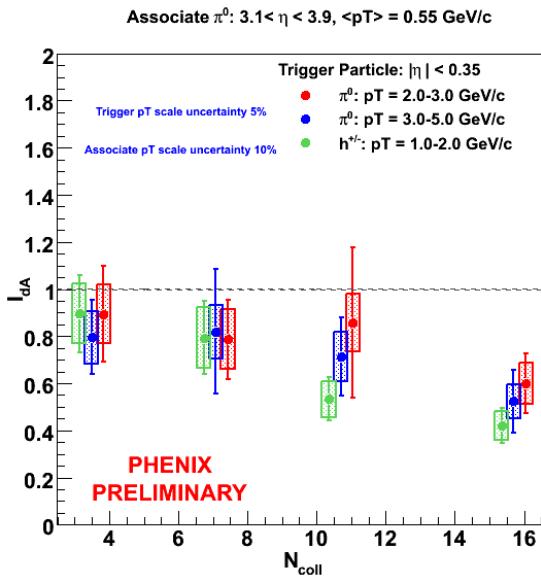


Forward Δφ Di-Hadron Correlations in PHENIX

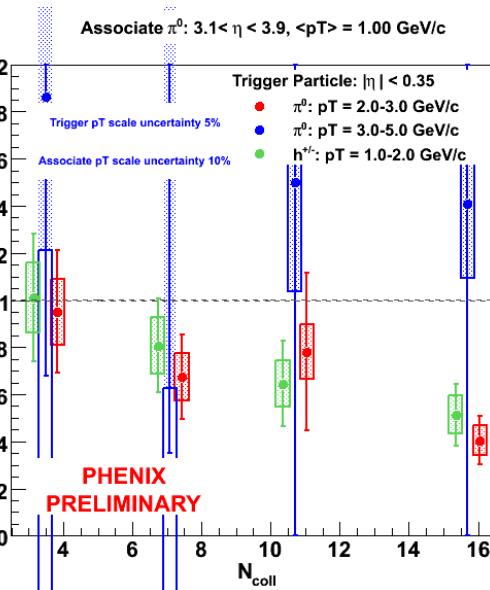


I_{dA} vs p_T^a

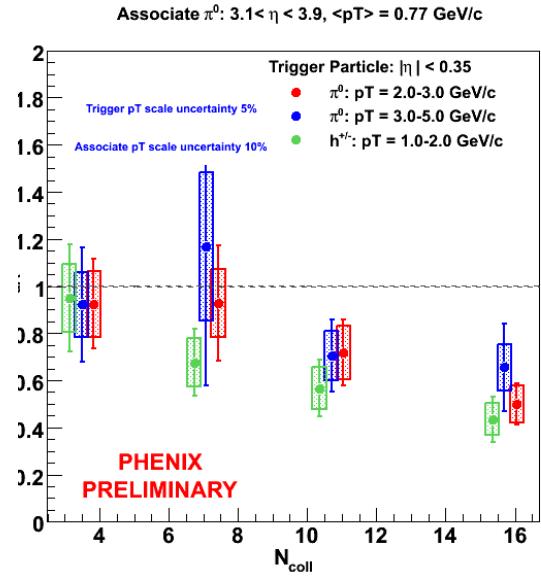
$$\langle p_T^a \rangle = 0.55 \text{ GeV}/c$$



$$\langle p_T^a \rangle = 0.77 \text{ GeV}/c$$

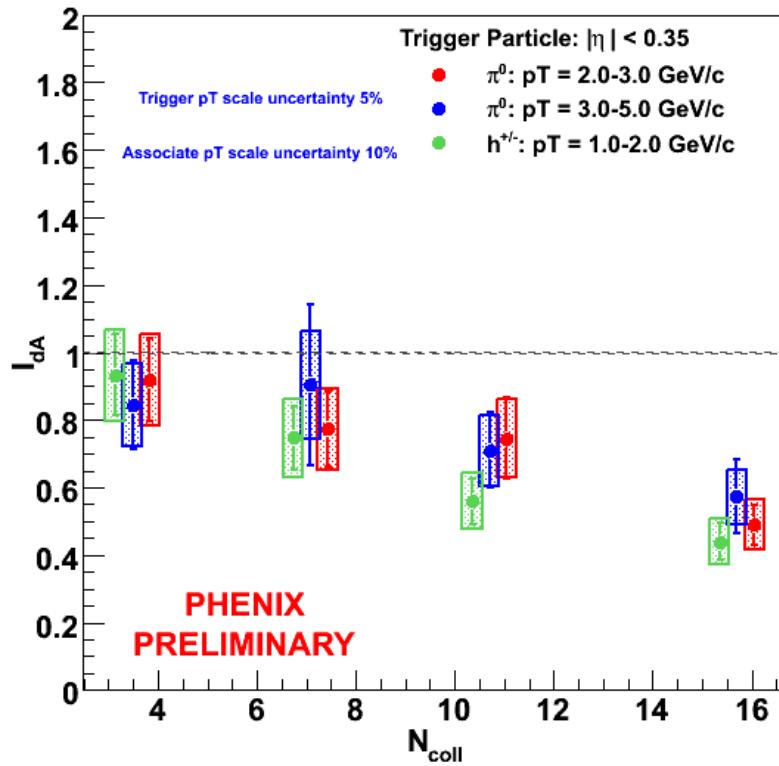


$$\langle p_T^a \rangle = 1.00 \text{ GeV}/c$$

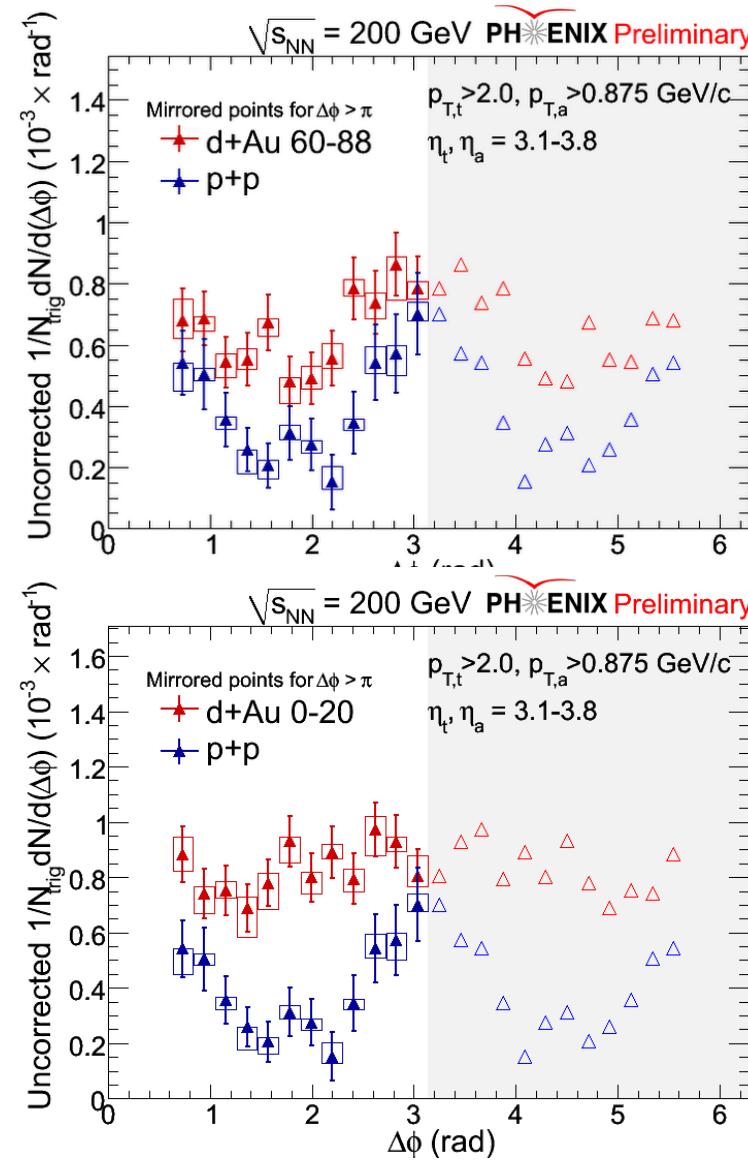
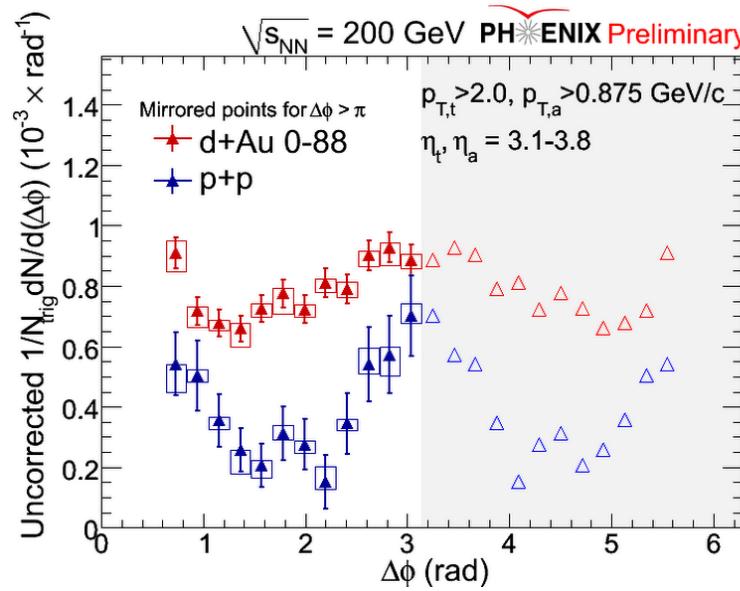


I_{dA} with 3 Trigger Particle Bins

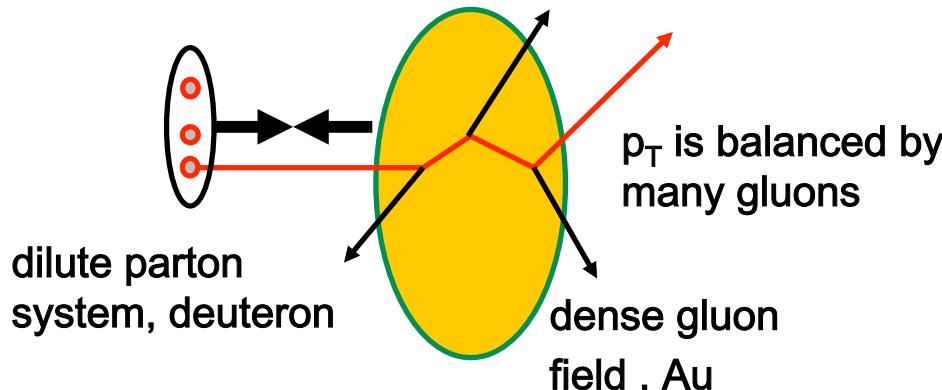
Associate π^0 : $3.1 < \eta < 3.9$, $pT = 0.45\text{-}1.59 \text{ GeV}/c$



Comparison of Correlation Functions



Probing for Saturation Effects with Hadron-Hadron Correlations in d+Au



Idea:

Presence of dense gluon field in the Au nucleus leads to multiple scattering and parton can distribute its energy to many scattering centers → “Mono-jet signature”. D. Kharzeev, E. Levin, L. McLerran, Nucl.Phys.A748:627-640,2005

Experimental signature:

Observe azimuthal correlation between hadrons in opposing hemisphere separated in rapidity

- widening of correlation width of d-Au compared to pp?
- reduction in associated yield of hadrons on the away side

→ Upgrades

Electromagnetic forward calorimeters added to PHENIX (MPC) for 2008 d +Au run.

- di-hadron correlations at the lowest possible x for forward-forward correlations !



PHENIX Muon Piston Calorimeter

Technology → ALICE(PHOS)

PbWO₄
avalanche photo diode readout

Acceptance:

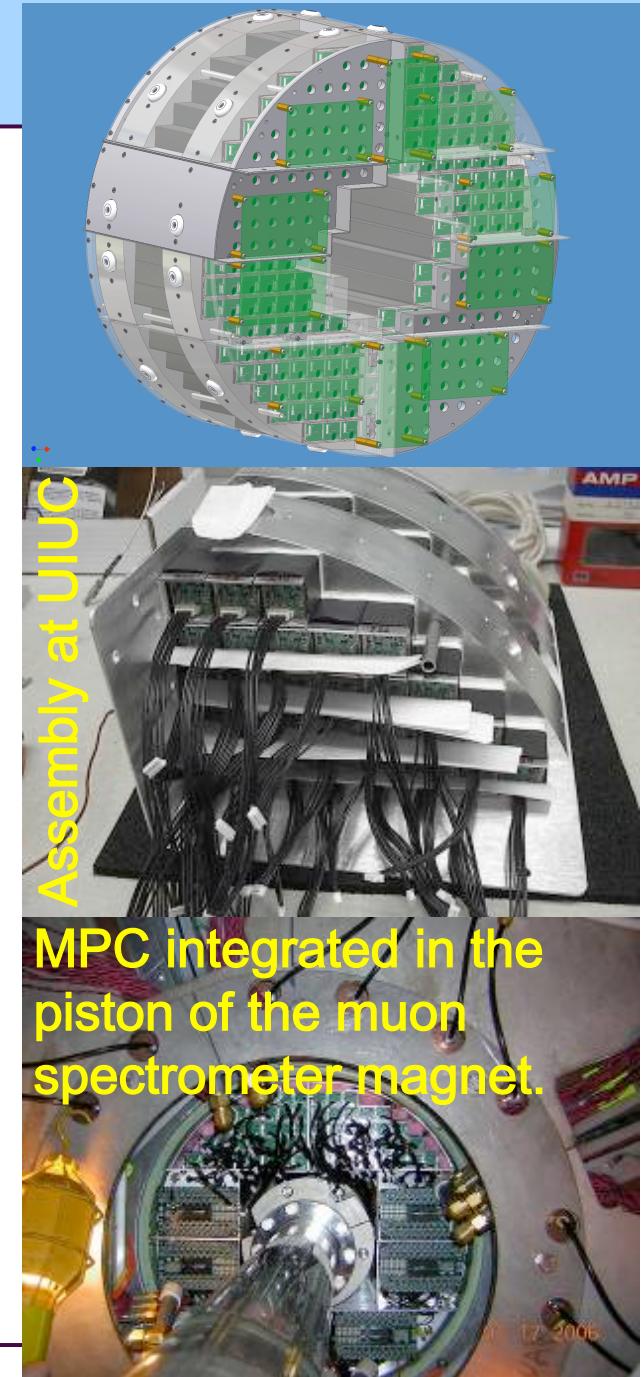
$$3.1 < \eta < 3.9, \quad 0 < \varphi < 2\pi$$

$$-3.7 < \eta < -3.1, \quad 0 < \varphi < 2\pi$$

Both detectors were installed for 2008 d-Au run.



Forward $\Delta\phi$ Di-Hadron Correlations in PHENIX



MPC History

South



North

Initial Installation
192 Towers



Run 06, pp: 200, 62 GeV

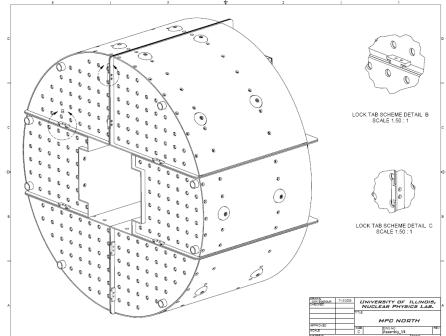


Run 07, AA: 200 GeV



Run 08, dA, pp: 200 GeV

Upgrade:
196 Towers
New Monitoring
System (N+S)



New Detector:
220 Towers



Light Calibration Box

Big thank you to Jimmy LaBounty



Why Forward in d+Au?

- Forward \rightarrow Low x

$$x_{g,Au} = \frac{p_{T1}e^{-y_1} + p_{T2}e^{-y_2}}{\sqrt{s}}$$

- Probe low- x gluon distribution in Au nucleus

- Suppression of particle yields expected due to extremely high gluon density

- Gluon saturation

- Saturation momentum goes like $Q_s^2 \sim \frac{A^{1/3}}{x^\lambda}$

- Need jet $p_T \sim Q_s$ to observe effects

- Shadowing effects

- Rapidity Separated Jets

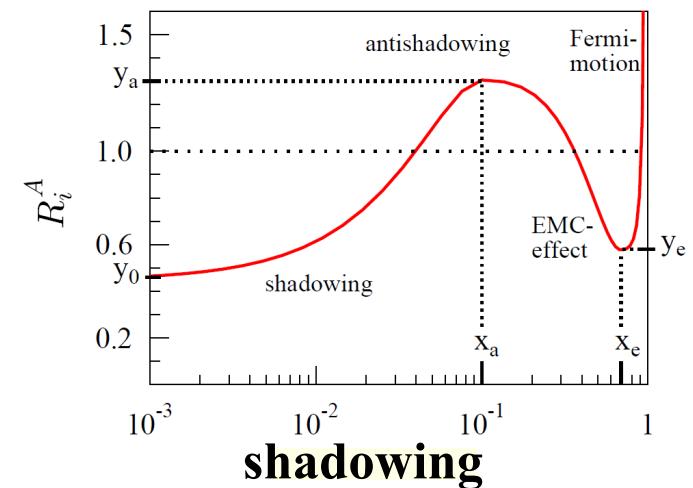
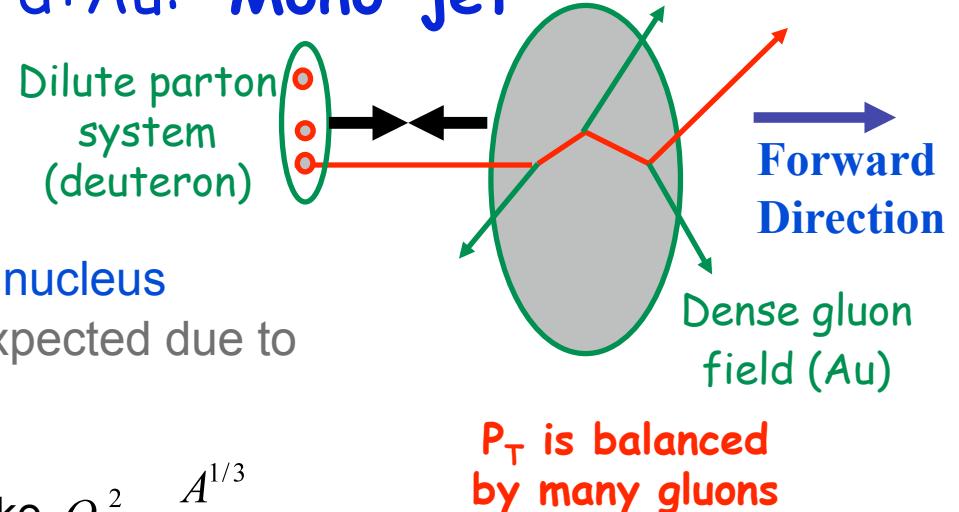
- BFKL evolution, a.k.a Quantum Evolution, produces Mueller-Navelet Jets

- Larger rapidity gap between jets \rightarrow larger probability for emitting gluons \rightarrow decorrelation in 2 ptcl $\Delta\phi$ distribution

- Experimental Program: Scan different $\Delta\eta$ separations for jets and look at low- x

d+Au: Mono-jet

Dilute parton system (deuteron)



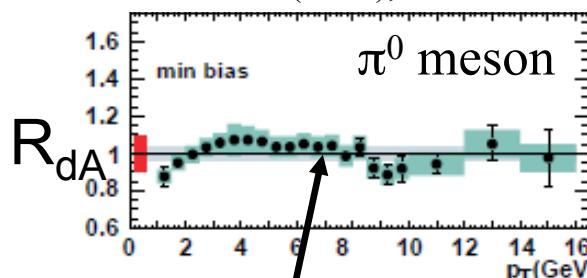
Nuclear Modification of Hadrons in d+Au

**Nuclear
Modification
Factor:**

$$R_{dAu} \equiv \frac{1}{\langle N_{coll} \rangle} \frac{d^2N^{d+Au}/dp_T d\eta}{d^2N^{p+p}_{inel}/dp_T d\eta}$$

PHENIX $|\eta| < 0.35$

PRL 98 (2007), 172302



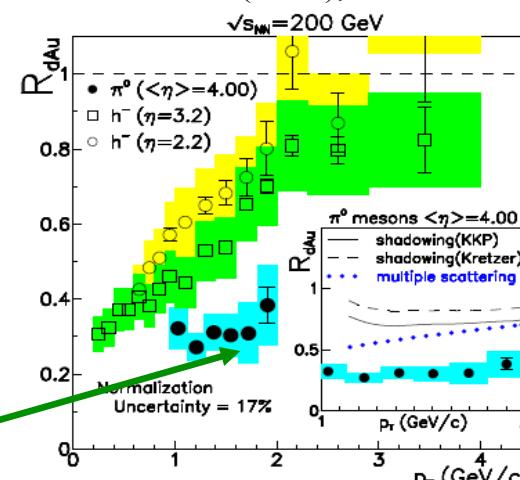
R_{dA} is 1 at $\eta=0$

R_{dA} is suppressed at forward η

Why? →

STAR, BRAHMS Forward η

PRL 97 (2006), 152302



Gluon Saturation?

Cronin + Shadowing + E-loss?

Need more measurements → $\Delta\phi$ Correlations

CGC expectations

Kharzeev, Kovchegov, and Tuchin,
Phys.Rev.D68:094013,2003

